SPATIAL PATTERNS AND MAXIMUM POWER IN ECOSYSTEMS

BY
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by

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Chairman: Howard T. Odum
Major Department: Environmental Engineering Sciences

Studies of dynamic systems have shown that oscillations in time and space are related, both being generated by nonlinear, pulsing behavior that is derived from the mathematics of energy processing. Similar mathematics exist in chaos theory, bifurcation theory, and catastrophe theory. Production-consumption models that simulate pulsing properties of ecological systems are of this class. This dissertation examines the spatial patterns and energetics of autocatalytic and pulsing models as a paradigm for ecological and general systems. Configurations were tested with steady or varying resource availability for ability of the model systems to maximize power as the criterion for utility and success. The spatial distribution of gaps generated by simulations was compared to that observed in rain forests.

Models studied included (a) aggregated, single-compartment autocatalytic designs; (b) parallel production-consumption design; (c) production-consumption-recycle

designs; and (d) multiple cell spatial models each with a unit model but interconnected in different ways.

Models with autocatalytic feedbacks utilized more power than the same models with only linear pathways. Percent power used increased with increasing available power.

Production-consumption models show multiple steady states with pulsing behavior as a transition between two steady states. Localized maxima of power use occur during pulsing but the overall power use is related to input power.

Spatial patterns of production and consumption in spatial models were related to input energy patterns, the degree of connectivity between the individual cells in the model, and the hierarchical level of intercell connections. Large variations in patterns were accompanied with small changes in power utilized.

Edges of a spatial system can act as a source or sink for energy depending on the relationship between available energy inside and outside the boundaries and the degree of connectivity along the edges.

Basic autocatalytic production-consumption-recycle models with different spatial conditions organize different spatial patterns while generating near total utilization of available power. The wide variety of spatial patterns results from dynamic adaptations for maximizing power for different spatial conditions. The simulation results resemble patterns in nature often attributed to random indeterminancy.

CHAPTER 1

INTRODUCTION

Ecosystems develop patterns in time and space. Some of these patterns are generated by pulsing oscillatory processes. What sorts of interactions, organization and structure in an ecosystem lead to pulsing behavior, and how does this behavior affect the use of energy? What types of spatial patterns develop when ecosystems are influenced by pulsing in time and space? What are the energy implications of different pattern forming processes in ecosystems? What are the effects of pulsing on succession, competition, frequency response of producers and consumers, and coupling with external pulses?

This dissertation uses general systems models to analyze the effects of pulsing on pattern formation and overall power use as systems develop, build structure and organize in time and space. Simulation models using general systems principles and based on real ecosystems were used to test the role of pulsing behavior of consumers in organizing ecosystems over time and space. Data from a tropical ecosystem were used to calibrate pulsing and spatial models.

Historical Perspective

Previous Models of Pulsing Patterns in Time and Space

In many fields from chemistry, physics, and biology to astronomy, there are a variety of models, methods and techniques to describe and study systems that have discontinuities or other rapid fluctuations in their behavior. Some of these are catastrophe theory (Thom 1975), bifurcation theory, synergetics (Haken 1977a,1977b,1979), dynamical system theory (Rosen 1970), chaos and order (Prigogine 1980,1984, and Schaffer and Kot 1985), pulsing (Lotka 1920 and Odum 1982), pattern recognition, and morphogenesis (Meinhardt 1982). In all of these, processes being described are parts of nonlinear thermodynamically open systems. Energy constraints on these types of systems have not previously been well studied.

In the past, efforts to describe systems using classical thermodynamics centered on closed systems near equilibrium or open systems near steady state. In such systems, available energy is small. These approaches using equilibrium thermodynamics could not account for the behavior of many systems (Odum 1983, Prigogine 1984, Schaffer and Kot 1985).

Data with statistical anomalies are often difficult to analyze and methods are sometimes used to minimize fluctuations (Platt and Denman 1975). Systems that have aperiodic behavior, a great deal of noise, or time dependent changes in variance are not well suited to the normal

statistical methods. These 'unusual events' can be important in understanding how a system works (Weatherhead 1986).

Frequency analysis has been used for some time to study periodic behavior of systems (Platt and Denman 1975, and Emanuel, West and Shugart 1978). Fourier transformations decompose the output or behavior of a system into an additive series of sinusoidal processes. The variance is partitioned into a set of frequencies that when combined gives the output being measured. Aperiodic behavior or systems with known nonlinear components may also be studied with these techniques, but the results are often not useful. Some nonlinear systems with behavior described as 'chaotic' have frequency domain variance as noisy as the time domain variance (Abraham and Shaw 1984a, 1984b).

Pattern Formation

Patterns in natural systems range from the smallest molecular patterns of motion to the placement of the stars and galaxies in the universe. One of the most intriguing aspects of pattern formation is the similarity of patterns at differing time scales and sizes. From a systems point of view this would lead one to suspect that the processes are similar at each scale.

Chemically reacting systems give rise to various types of patterns (Bray 1921, Nicolis and Prigogine 1969, Winfree 1973, Haken 1977a, 1977b). The Belousov-Zhabotinski reaction, which makes fascinating patterns, is a simple

oxidation-reduction reaction involving malonic acid, bromate and a cerium catalyst (Winfree 1973). An example of the time and spatial development of this reaction is shown in Figure 1a.

Morphological development in biological systems has been studied and modeled by Meinhardt (1982). Patterns form when autocatalytic growth in a system is combined with lateral inhibition (negative spatial feedbacks). Once autocatalytic activity starts, there must be a longer range negative feedback (spatial inhibition of the spread of this autocatalysis) or the whole system will pulse in a burst of autocatalytic consumption. This sets up spatial chemical gradients along which morphogenesis is thought to occur (Figure 1b).

Hilborn (1979) experimented with predator-prey models based on an aquatic ecosystem. Hilborn's model had 100 spatial cells arranged in a linear chain with the ends connected to form a circle. Both predators and prey were allowed to diffuse across cell boundaries. The model was simulated with initial conditions set so that all cells had prey but only one cell had a predator. The model (Figure 2a) was allowed to iterate for 1000 time intervals, generating the pattern seen in Figure 2b. Further experiments showed that there was no tendency towards equilibrium in longer runs of the model.

The spatial development of insect eyes and insect legs has been modelled by Ransom (1981) using an autocatalytic

Figure 1. Spatial patterns based on chemical reaction mechanisms.

(a) Spatial patterns generated by Belousev-Zhabotinski chemical reaction (Prigogine 1980).

(b) Spatial patterns generated by simulation model used to describe morphogenesis (Meinhard (1982).

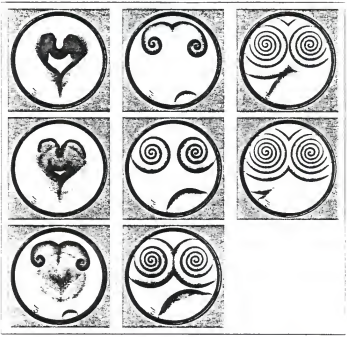


Figure 2. Hilborn's (1979) spatial model.

(a) Energy diagram of individual cell model

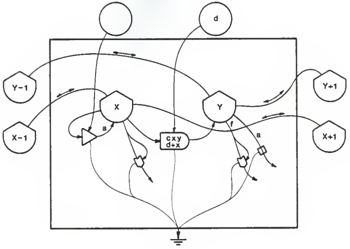
Equations for simulation model.

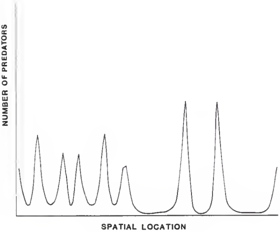
```
dX(i)=a*X(i) - b*X(i)*X(i) - (c*X(i)*Y(i)/(d+X(i)))
       +h*X(i+1) +h*X(i-1) - 2*h*X(i)

dY(i)=-e*Y(i) - f*Y(i)*Y(i) + (g*X(i)*Y(i)/(d+X(i)))
       +k*Y(i+1) +k*Y(i-1) - 2*k*Y(i)
```

where i is the number of the subsystem in a linear loop.

(b) Simulation results of linear series of unit models showing level of predator vs distance around loop.


d
Y-1
Y
Y+1
X
X-1
X+1
a
cxy
d+x
f
a


NUMBER OF PREDATORS
SPATIAL LOCATION

model. By allowing cells in the model to divide and migrate within given constraints, the model developed patterns similar to those in real insects. The model allowed simple random cell division with movement constrained to a hexagonal direction away from the center of the cell division.

Sergin (1978, 1979, 1980) studied the oscillatory behavior of long term climate variations using models that combine linear and nonlinear interactions of the heat capacities of the oceans and polar ice sheets. The period of the climatological events in these models is on the order of 10,000 to 100,000 years. The model of global temperatures varies in its behavior from steady state to oscillations based on small changes in areal coverage of continental ice sheets.

Pattern formation based on digital, rule based systems has been used to model biological systems. Examples such as cellular automata (Turing 1952 and Wolfram 1984) and a 'game of life' (Gardner 1970 and Poundstone 1985) generate complex spatial patterns from simple rules. The 'game of life' is generated on an N x N matrix where

1. Every active cell with two or three neighboring cells survives to the next generation.
2. Each active cell with four or more neighbors 'dies' from overpopulation. Every active cell with one or no neighbors 'dies' from isolation.
3. Each empty cell adjacent to three 'live' neighbors gives birth to a new cell.

Figure 3 is an example of the patterns generated from a simple five cell seed (R-pentomino) during 512 iterations. This pattern stabilizes (no more deaths and no more births) after 1103 iterations, although it is an oscillating steady state. Individual subsets of the final stable pattern oscillate.

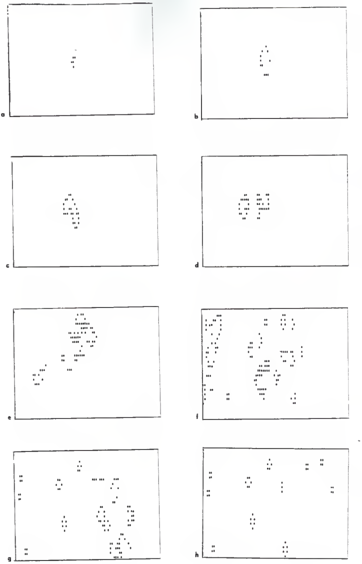
The 'game of life' model has some of the features of autocatalysis (or cooperative behavior). Two or three live cells are required for survival or birth of new cells. It also has the feature of diffusive inhibition because individual cells that move out from a population center can become isolated and die. This rule-based system has no energy constraint that governs development and thus gives no energy basis for pattern formation.

The common theme that runs through these examples is one of combined interactions of autocatalytic growth with some form of inhibition, diffusion or other mechanism for preventing the autocatalytic growth from spreading too rapidly. A concept that is sometimes misunderstood or misinterpreted is that the terms fluctuation (Prigogine 1980, 1984) and bifurcation theory (Pacault 1977) refer to a change in the kinetics of reacting components of a system. This change in kinetics gives rise to the oscillations or pulses in the output.

The models in this dissertation also use combinations of autocatalytic and diffusion (linear) pathways to study

Figure 3. The development of spatial patterns among cells based on simple r-pentamino initial condition (a) in 'a game of Life' simulation.

(a) Time = 0
(b) Time = 8
(c) Time = 16
(d) Time = 32
(e) Time = 64
(f) Time = 128
(g) Time = 256
(h) Time = 512


a
b
c
d
e
f
g
h

the possible mechanisms and energy consequences of pattern formation in ecosystems.

Concepts of Pulsing, Patterns and Power

Maximum Power in Systems

Although in the last century Podalinsky, Ostwald and Boltzman suggested energy use controlled system performance (Martinez-Alier 1987), Lotka (1922) made a more definitive statement. He stated that evolution proceeded in such a direction as to make the total energy flux through the system a maximum compatible with the constraints on the system. He related this to Ostwald's (1892) idea of all possible energy transformations, that one takes place which brings about the maximum transformation in a given time.

A theory of minimum entropy generation was put forth by Prigogine (Prigogine and Wiaume 1946) that a system evolved toward a stationary state characterized by the minimum entropy production compatible with the constraints on the system. He has since called this a failure and probably a special case of systems near equilibrium (Prigogine 1984). Prigogine (1978, 1980, 1982; Prigogine and Stengers 1984) now deals with systems far from equilibrium that have dynamic and oscillatory behavior. He has not postulated any definite theory about the energetic consequences of these types of systems.

Odum and Pinkerton (1955) proposed that natural systems tend to operate at that efficiency which produces a

maximum power output, a general restatement of Lotka's original idea of maximum energy flow but with an important distinction. Odum (1971, 1982, 1983a, and 1983b) further clarifies maximum power as useful power where 'use' is feedback of the product of energy use to amplify other pathways.

In describing cycles of life, death and regeneration, Calow (1978) has found that although Lotka's principle holds, there seem to be no a priori grounds for placing restrictions on how this use of energy should be achieved. He further stated that selection would have shifted in the course of time from one of maximizing speed to maximizing efficiency. This is a restatement of the strategy of ecosystem development utilizing r and K growth (Odum 1969).

Jantsch (1980) suggests than maximum engagement in matter (i.e., energy storage) and maximum process intensity (i.e., entropy production) are criteria for ecosystem stability. Non-equilibrium structures thus come about by fluctuations in the mechanisms which result in modifications of the kinetic behavior of these structures.

Design for Maximum Power

The important question here is how do systems build structure in order to maximize utilization of available power. Odum's theory (1971 and 1983) is that by feeding back energy (derived from structure that is being built) reinforcement occurs that increases efficiencies and energy

flow into the structure. Mechanisms must develop that build structure to capture the most energy possible. These feedback structures then have a prior energy use embodied in them (emergy, after embodied energy, of a structure has been defined as the total amount of energy used in developing these structures (Odum 1983 and 1986)). This dissertation looks at some of the possible kinetic pathways that feed back to process energy and the energetics of these pathways.

Pathway Configuration

A simple model demonstrates several ways in which useful power can be increased (Figure 4, see description of symbols in Figure 9). This model is a single storage with autocatalytic production drawing on a flow-limited energy source (an energy source with constraints on the pathway, limiting the amount of energy that can be delivered).

The efficiency of a pathway can be increased if less energy is fed back to gain more energy. For a simple autocatalytic system (Figure 4a and 4b) this can be done by either using less energy to gain the same inflow (changing the value of K2 in the model) or by increasing the inflow for the same feedback (increasing K1 while concurrently decreasing K3). Because there are thermodynamic limits on any process, it may not be possible to improve designs to increase energy flows beyond thermodynamic limits.

The first law of thermodynamics requires the conservation of energy. This implies the following constraint on the production process of the model (Figure 4).

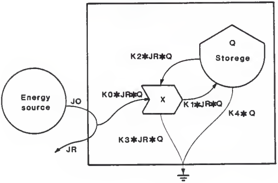
Figure 4. Basic autocatalytic model with flow-limited energy source.

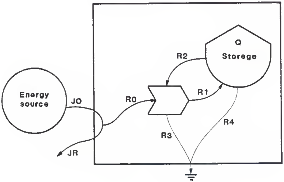
(a) Diagram with kinetic terms

```
dQ = K1*JR*Q - K2*JR*Q - K4*Q
JR = J0 / (1+K0*Q)
```

(b) Diagram with flow terms

```
R0 = K0*JR*Q
R1 = K1*JR*Q
R2 = K2*JR*Q
R3 = K3*JR*Q
R4 = K4*Q
```


Q
Storege
K2*JR*Q
Energy source
JO
K0*JR*Q
X
K1*JR*Q
K4*Q
K3*JR*Q
JR


Q
Storege
R2
Energy source
JO
R0
R1
R4
R3
JR

$$K\emptyset * Jr * Q + K2 * Jr * Q = K1 * Jr * Q + K3 * Jr * Q \qquad (1)$$

Substitute R (flow) terms as abbreviations for terms in equation (1):

$$R\emptyset + R2 = R1 + R3 \qquad (2)$$

Inputs of energy of any process must equal the outputs. Efficiency is defined as:

Efficiency = (Output of useful power)/Inputs

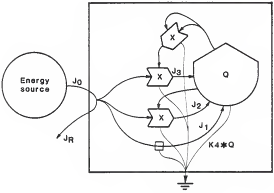
or in terms of our equation:

$$\text{Efficiency} = R1/(R\emptyset+R2) \qquad (3)$$

where R3 is waste heat generated in the process (required by the second law of thermodynamics). Because R3 cannot be zero, there is a natural upper limit to the efficiency of any process.

Another method to increase energy flow from a flow limited source is to have multiple pathways capture available energy, each effective at a different energy level (Figure 5). Multiple pathways (J1,J2,J3) use stored energy to build structures to capture available energy. A linear, donor-controlled pathway (J1) requires little structure and employs no feedback in order to capture energy, but has severe limitations (its efficiency cannot change) due to the dependency on the energy source. An autocatalytic pathway (J2) feeds back embodied energy (structure built by the system) to draw in more energy. The quadratic pathway (J3) is a co-operative phenomenon in which the structure of the system is interacting with itself to feed back embodied energy to draw in more power. A system that develops such

Figure 5. Basic multiple path model. Three input pathways represent different feedback regimes: linear (J1), autocatalytic (J2), and quadratic (J3).


Energy source
J_0
J_R
X
X
X
J_3
Q
J_2
J_1
K4*Q

higher order feedback pathways may exhibit a greater rate of use of available energy.

This added quadratic pathway is available to utilize any energy left after the efficiency is raised to the upper limit for the autocatalytic pathway. This is a mechanism that can draw in energy that would normally be unavailable to the system. The quadratic pathway may have a high cost to develop and maintain this pathway but it enhances overall use of that extra energy by the whole system. This may give a competitive edge in some circumstances over systems without higher order pathways, particularly when available energy may be fluctuating. Available power will be increased by switching from one pathway to the other depending on the energy source. Some pathways are more efficient at low energy levels while others are more efficient at high energy levels, thus allowing such systems to efficiently utilize fluctuating power sources.

Pulsing and Patterns in Ecosystems

Succession and Disturbance

Any climax state is eventually interrupted by disturbances that generate patches in which succession is reinitiated. The gaps in a forest may be generated by local outbreaks of consumers within the forest, tree mortality, or outside disturbances such as fires, hurricanes, volcanic activity, and landslides (Runkle 1985). The role of the landslide as a gap-forming mechanism has been described in

both temperate forests (Oliver 1981, and Veblin 1985) and tropical forests (Garwood 1979, and Leigh et al. 1982).

Disturbances (i.e., pulses) to an ecosystem can be generated from within or can come from outside the boundaries of an ecosystem and may vary in frequency and amplitude. The ability of an ecosystem to utilize available resources and adapt to these disturbances depends on the storages, structures and interactions within an ecosystem (Odum 1983). Hierarchical mechanisms may develop that capture and process energy at various levels and result in utilization of energy over a wider variety of input levels. Some mechanisms of interaction between parts of the ecosystem were studied in this dissertation to understand how systems may converge energy transformations and feedback controls to organize for higher productivity.

No unified theory of succession presented to date can be regarded as widely accepted (Anderson 1986). Horn (1976) wrote 'The sweeping generalization that can be safely made about succession is that it shows a bewildering variety of patterns.' Even the definitions of succession are widely varying. In this dissertation succession is regarded as a dynamic process in which the composition of an ecosystem changes through time, building structure and processing energy. This process eventually stabilizes in a climax from which there is a regression or loss of that structure due to disease, fire, treefall or other events. Seeding from another ecosystem or from storages in the soil from the

previous ecosystem regenerates a facsimile of the original ecosystem through a sequence of unidirectional stages that reaches a steady state system called a climax. This climax may be arrested at some point and in some cases succession may cycle between several stages. This definition is broader than most but is an attempt to describe the whole process instead of the more narrow 'growth-phase' definition.

Regression from a climax state may occur in several ways. In some cases it comes about as a pulse of consumption from within the ecosystem boundaries such as treefalls, landslides or disease outbreaks. It can also come about from disturbances from larger outside events such as hurricanes or drought. The frequency and amplitude of these disturbances tend to be inversely correlated: larger disturbances occur less frequently than smaller ones. This phenomenon is referred to as a hierarchy of disturbances (Bennett and Chorley 1978). The interaction of these disturbances along with the internal fluctuations may lead to the 'bewildering variety of patterns' to which Horn refers.

Edges

Ecosystems can generally be broken up into subsystems that have uniform characteristics. These subsystems have boundaries where the composition changes from one particular type to another. The development of these edges may occur where differing types of energy interact with ecosystem components to generate patches and zones of transition. The

presence of many spatially distributed patches may be due to the production-consumption pulsing of components in the ecosystem.

Hierarchies and Patches

The frequency of disturbance based on internal cycles has been shown to be from 200-500 years in a variety of ecosystems (Emanuel, West and Shugart 1978, Runkle 1985). Distribution of disturbances over time varies from fairly constant low amplitude disturbances to long-period, high amplitude disturbances. The successional changes due to disturbances may be related to the size and scale of the disturbance (Peet and Christensen 1980, Peet 1981).

Brokaw (1982a, 1982b, and 1985a) found a hierarchical distribution in gap sizes in a tropical rain forest at Barro Colorado Island (Figure 6a). The area per size class is plotted vs. the size class (Figure 6b). This relationship may be important in determining patch dynamics. Brown (1980) suggested that size class distributions may be related to the emergy per size class (the emergy per size class is also related to the area per class). Brokaw calculated the turnover rate for the forest, based on the gap formation, to be from 85 to 128 years depending on the minimum size of the lowest class used.

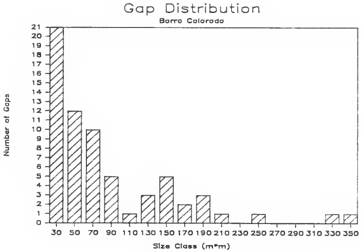
Models

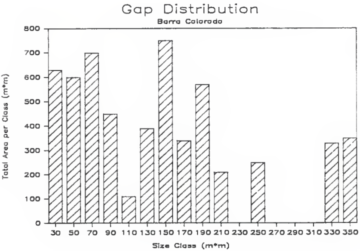
The simulation models used to study ecosystem behavior generally fall into two classes (Shugart 1984). One of these

Figure 6. Size class distribution of gaps formed in tropical forest at Barro Colorado (Brokaw 1982).

(a) Distribution of gaps by diameter of gap.

(b) Distribution of gaps by area in gap.


Gap Distribution
Barro Colorado
Number of Gaps
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
30 50 70 90 110 130 150 170 190 210 230 250 270 290 310 330 350
Size Class (m*m)


Gap Distribution
Barro Colorado
Total Area per Class (m*m)
800
700
600
500
400
300
200
100
0
30 50 70 90 110 130 150 170 190 210 230 250 270 290 310 330 350
Size Class (m*m)

is based on the nonlinear 'Lotka-Volterra equations' and generally does not include outside influences. The other uses forced linear systems of differential equations and does have inputs from outside the system. Neither of these methods typically contains any spatial considerations and both deal with systems near equilibrium. Systems near equilibrium tend to move toward that equilibrium and are characterized by spatial uniformity (Prigogine 1984 and Field 1985).

In this study, open non-equilibrium models are developed that combine non-linear and oscillatory interactions between production and consumption with outside forcing functions that provide resource controls. A pulsing, hierarchical model of production and consumption is used to generalize about succession and regression. Spatial interactions generated by this model are studied to understand the energetic and kinetic basis for pattern formation in ecosytems.

Gap Models and Patch Dynamics

Several previous studies based ecosystem models on disturbance gaps. The JABOWA forest simulator model by Botkin, Janak and Wallis (1972) keeps track of the birth, growth, and death of a group of trees from seedlings on to maturity within a certain gap size. Subroutines are used for crowding, shading, and response to individual nutrients and energy sources. The simulation then allows the gap to

develop a distribution of trees based on all of the input parameters. These gap models generally do not account for any outside disturbances that generate gaps.

Various gap models (Phipps 1979, Shugart and West 1980, Shugart, Mortlock, Hopkins, and Burgess 1980, Shugart and Noble 1981, Doyle 1982, Doyle, Shugart, and West 1982, Shugart 1984, and Pickett and White 1985) have been utilized to study forested ecosystems around the world. These models have various gap sizes ranging from $100m^2$ to $833m^2$.

Spatial Systems and Models

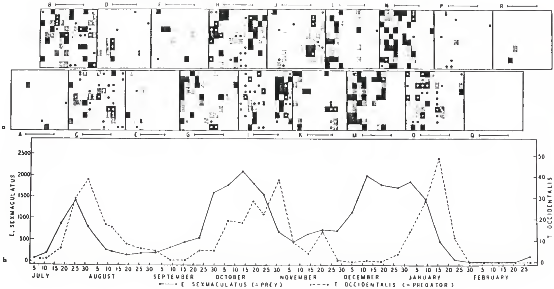
A spatial predator-prey insect microcosm was used by Huffaker (1958) to study two species of mites. The prey mite fed on oranges while the predator mite fed on the prey. In one set of experiments, the oranges were distributed in a 10x12 grid with partial barriers between the oranges and one prey placed on each of the 120 oranges. Five days later 27 predators were dispersed on the oranges. The resulting dynamics in populations both over time (8 months) and space are shown in Figure 7. In other experiments with oranges in different arrangements, the oscillatory behavior was not seen. Huffaker concluded that the predator-prey oscillation would only occur when there was migration from the outside or a sufficiently complex spatial arrangement of prey and barriers to allow localized growth of the prey followed by consumption by the predator.

Figure 7. Mite predator prey experiment (Huffaker 1958).

(a) Spatial distribution.
Prey concentration is shown by intensity of small blocks (darker is higher density) and predator locations are marked with small circles.

(b) Time series of total predators and prey in spatial area. Letters on graph refer to the time series for the spatial display next to the letter.

Prey: 0-5 nil density (white); 6-25 low density (light stipple); 26-75 medium density (horizontal lines); 76 or over, high density (solid black). Predator: 1-8 (one white circle).



In high altitude balsam fir forests in the northeastern United States, waves of tree loss and regeneration are thought to be formed by an interaction of the prevailing wind with the larger mature trees that are exposed along the gap-wave (Sprugel and Bormann 1981, and Sprugel 1984). The wind in this case acts to organize the disturbance cycle that occurs normally in this type of forest into a spatial wave pattern instead of randomly occurring patches.

The 'ohi'a dieback phenomenon in the rain forests of Hawaii (Mueller-Dombois 1980) is a case of localized loss of trees in the forest not due to disease or insect pest. It was postulated that the effects were due to local soil moisture loss arising from some climate instability. Reproduction of the 'ohi'a was adequate enough to regenerate the forest after the dieback, thus providing a way for this shade intolerant species to become the primary canopy species without further succession. Climatic variability was thus used to an adaptive advantage.

Spatial modelling of ecosystems can be done in several different ways. By using a model based on the FORET simulation model (Shugart and West 1977) and spatially distributing the output of the model according to flooding conditions and hydroperiod, Pearlstine, McKellar and Kitchens (1985) suggested possible species changes due to changes in the hydroperiod caused by a river diversion in South Carolina. In this case the number of individual subcell models was kept small and the spatial distribution was based

on a combination of terrain relief, hydrology, and correlated output from the simulation model.

Another approach to spatial modelling is to divide the area into individual cells with a representative model in each cell with some interaction terms among the individual cells. This is the approach Costanza (1979) used in modelling the economic development of South Florida.

Simulations with individual models for each cell have certain advantages, because the interaction of neighboring cells influences the outcome. A serious disadvantage where the number of cells is large is the immense amount of computer time required for the simulations. By making the cell size larger this can be avoided, but loss of spatial detail occurs as the cell size increases. The sub-cell distribution modelling technique used by Pearlstine et al. (1985) has just the opposite advantages and disadvantages. The time requirements for simulation do not necessarily increase as the area of cells is increased, but individual intercell interactions are lost.

Plan of Study

Objectives

This study of energy use and pattern formation with production consumption models has several parts:

First, the energetics of different pathway configurations were tested using a series of minimodels. These models were manipulated to determine the energy use of

systems with different production and consumption kinetics and different combinations of components.

Second, a generalize production-consumption minimodel calibrated with tropical rainforest data was used to study the energetics of pulsing behavior.

Third, spatial pattern formation was investigated using the pulsing production-consumption model as subunits in a spatially distributed format. The spatial effects and energy implications of various patterns of energy inputs, edges, and lateral connectivity were determined.

These spatial simulations included several types of inter-block exchange. Hierarchical relationships are represented in these models when each consumer component interacts with more than one producer unit. The distribution of gaps developed by simulations was compared with gaps in the tropical rainforest in Puerto Rico.

Finally, insights and hypotheses were developed about behavior of ecological systems.

Data site: Luquillo Rainforest, Puerto Rico

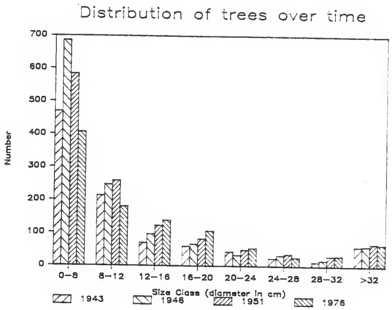
Data from the Lower Montane Rainforest in the Luquillo Mountains of Puerto Rico were used to compare some of the spatial simulations of pulsing and patches. Extensive studies on this forest were published previously (Odum and Pigeon, 1970).

Changes in structure and composition of a plot of tropical rain forest near El Verde in Puerto Rico over a period of 30 years were reported by Crow (1980). Data

included size class distributions taken in 1943, 1946, 1951 and 1976 (Figure 8). It can be seen that there is a shift over time in the different size classes. The peak year for the 0-8 cm class is 1946 while the peak in the 8-12 cm class occurs in 1951 and the peak in the next three size classes occurs in 1976. The smallest number in the lower two classes also occurs in 1976. The last severe hurricane struck Puerto Rico in 1932, and this movement through the size classes appears to be the growth and development of an age class of trees that grew back after the hurricane. The hurricane in this case acts as an organizing disturbance to reset succession of patches on a large scale.

The models simulated include the main integrative mechanisms observed in ecosystems for coupling production and consumption of spatially distributed units. Energy use of these configurations was obtained from the simulations to test the hypothesis that commonly observed organizational designs with a successional regime that alternates production and consumption, tend to maximize system power in the long run.

Figure 8. Size class distribution over time of plot of trees in tropical forest at El Verde (Crow 1980).



Distribution of trees over time
700
600
500
400
300
200
100
0
Number
0–8
8–12
12–16
16–20
20–24
24–28
28–32
>32
Size Class (diameter in cm)
1943
1946
1951
1976

CHAPTER 2

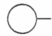
METHODS AND MODELS

Ecosystem concepts, configurations, and models were represented with energy circuit language from which simulation programs were derived. The energy circuit language, developed by H. T. Odum (Odum 1971, Odum and Odum 1981 and Odum, 1983), is a symbolic language for modelling ecosystems and their components. Elements of storages, flows, and interactions in this symbolic language keep track of the laws of energy conservation. The energy diagrams also show the correct kinetic interaction between parts of the system. The level of aggregation or disaggregation that is needed to understand and model a system for a particular purpose can be achieved by drawing and revising diagrams using this energy circuit language. A diagram of most of the important symbols with a brief description of each is presented in Figure 9.

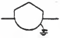
One of the benefits of using the energy circuit language is that it is possible to go from a conceptual model to the development of the differential equations needed to simulate the model in a few steps. Each of the pathways on the diagram represents a flow that in turn can be represented by terms in the differential equations that

Figure 9. Energy circuit language symbols (Odum 1983).

Energy circuit A pathway whose flow is proportional to the quantity in the storage or source upstream.

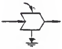


Source Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

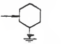


Tank A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable.

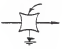
Heat sink Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system.



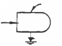
Interaction Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate.



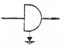
Consumer Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow.



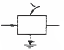
Switching action A symbol that indicates one or more switching actions.



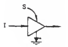
Producer Unit that collects and transforms low-quality energy under control interactions of high-quality flows.



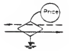
Self-limiting energy receiver (Chapter 10). A unit that has a self-limiting output when input drives are high because there is a limiting constant quantity of material reacting on a circular pathway within.



Box Miscellaneous symbol to use for whatever unit or function is labeled.



Constant-gain amplifier A unit that delivers an output in proportion to the input I but changed by a constant factor as long as the energy source S is sufficient.



Transaction A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed). Price is shown as an external source.

describe the changes in storage compartment (tank) values over time.

Simulation Procedures and Programs

The majority of the simulations in this dissertation were done in FORTRAN-4-PLUS on a Digital Equipment Corporation (DEC) PDP 11/34 with RSX-11M operating system. The graphical outputs of the simulations were displayed on a DEC VK-100 graphics terminal (General Image Generator and Interpreter or GIGI) connected to a Barco color monitor and DEC LA-34 Decwriter. The GIGI terminal has a 760x240 pixel resolution and can display up to eight colors on a color monitor. In order to facilitate the graphics programming needed in my simulation models, I developed a set of FORTRAN subroutines with a more natural calling sequence to execute the ReGIS (Remote Graphics Instruction Set use by the GIGI terminal) commands from the programs. This library of routines (GGLIB) is listed and documented in the Appendix.

Some of the goals of this dissertation were to examine the structure and function of systems in time and space and to determine how variation in coefficients may affect energy flows and storages of the systems. Graphical display programs were developed to project a simulated 3-D surface of the output of various state variables over time and over a range of input conditions. A special 3-D graphics display program was written to display the output of these model simulations (program PLOTZ, Appendix).

The spatial models are broken down into cells that show the concentration of a given parameter in the individual cell as a color block. For display on the color monitor this provides dramatic views of the model changes over time and space. In order to make hardcopy printouts a display character set was designed so the density of the dots in an individual cell was correlated to the color of the cell. This provided a way of screen-dumping the images to paper and achieving patterns on paper that were similar to the ones on the video screen (See Appendix for a listing of the character set).

Simulation Models

Minimodel Tests

First a group of minimodels were simulated to relate energy use to basic pathway designs. Then spatial models with these configurations were studied for energy use and pattern formation.

Three path minimodel

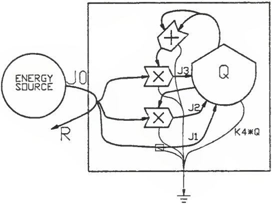
In order to understand how a system processes variable energy inputs, builds structure, and regulates or maximizes energy flows, a simple single tank model was simulated. The model is similar to the one described by Odum (1982) that has parallel pathways of different types competing for available energy (Figure 10). The model has a flow limited source connected to a single storage (tank) by three different pathways; a linear pathway (J1), an autocatalytic

Figure 10. Three pathway model used to test effects of various energy inputs on kinetic mechanisms.

Linear input:	J1=K1*R
Autocatalytic input:	J2=K2*Q*R
Quadratic input:	J3=K3*Q*Q*R

dQ=J1+J2+J3-K4*Q

R=J0-J1-K0*R*Q-K5*R*Q*Q


ENERGY SOURCE
J0
R
J3
Q
J2
J1
K4*Q

pathway (J2), and a quadratic pathway (J3). The tank has a linear drain.

The model represents a system that can change its use of three functional pathways to get energy. The linear pathway represents the energy flow that a system can receive without any feedback in this pathway, only pathway resistance to the flow. Because it is a donor controlled pathway, the system has no control on the flow. Diffusion pathways are an example of this type of energy flow. The linear pathway is very efficient because it takes almost nothing to receive the energy.

The autocatalytic pathway has a feedback from the system storage for interacting with an energy source to facilitate the capture of more energy. If energy is available to support the storage this pathway may lead to a competitive advantage over the linear pathway. The efficiency of the autocatalytic pathway depends on the energy source, the storage and the pathway coefficient. A pathway of this type has the capability of capturing more available energy.

The quadratic pathway has a self-stimulating feedback (see equation on Figure 10) from the storage to capture available energy. Examples of cooperative feeding that may fit this model are common in ecosystems such as pack hunting by some carnivores, cell and organ system interactions and the cooperative work by humans in developed nations.

This model was simulated in BASIC (program THREEPATH in Appendix) on a Digital Equipment Corporation (DEC) PDP 11/34 using a DEC VK-100 graphics terminal (GIGI). Measurements were made of the percent of the input power used while applying various levels of input power and varying the frequency of input power. Simulation runs were also made with one or more of the three pathways set to zero to determine the impact of the various pathways on the overall system behavior and power utilization.

In conjunction with the three path model in Figure 10, a similar model with the same inputs but with additional higher order drain pathways was simulated to determine the effects on total power usage (Figure 11). In any system that has crowding effects or high storage costs, these drain pathways may determine how the system processes energy. The model has a linear drain, an autocatalytic drain and a quadratic drain.

The basic three path model was tested for the effects of size and turnover time on the percent power used for various power inputs by varying the drain coefficient (K4 on Figure 10) in multiple simulation runs.

The percent power used when the three path model competes with individual storages with single pathways (Figure 12) was also simulated to see how the various pathways may help or hinder a system. The competitors are individual tanks with single pathways corresponding to the three pathways in the three path model.

Figure 11. Three pathway model with multiple drain pathways. Used to test effects of higher order drain pathways on threepath model.

Linear input:	J1=K1*JR
Autocatalytic input:	J2=K2*Q*JR
Quadratic input:	J3=K3*Q*Q*JR
Linear drain:	J4=k4*Q
Autocatalytic drain:	J5=K5*Q*Q
Quadratic drain:	J6=K6*Q*Q*Q

dQ=J1+J2+J3-J4-J5-J6
JR=J0-J1-K2'*J2-K3'*J3

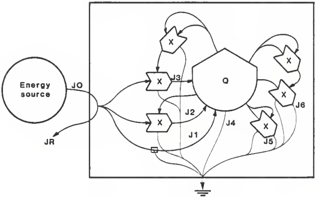

Energy source
JO
JR
X
X
X
X
X
X
Q
J1
J2
J3
J4
J5
J6

Figure 12. Three pathway model with individual competing units having single input pathways similar to combined model. Coefficients in Appendix.

Combination tank:

```
Linear input:            J1=K1*JR
Autocatalytic input:     J2=K2*Q*JR
Quadratic input:         J3=K3*Q*Q*JR

dQ=J1+J2+J3-K4*Q
```

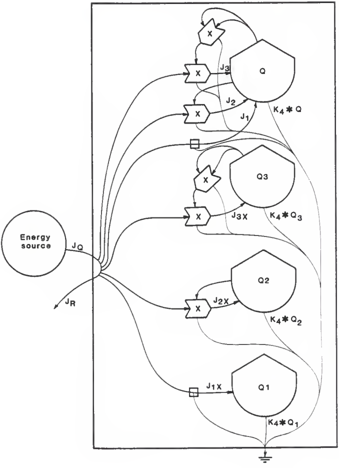
Single tanks:

```
Linear input:            J1X=K1'*JR
dQ1=J1X-K4*Q1

Autocatalytic input:     J2X=K2'*Q2*JR
dQ2=J2X-K4*Q2

Quadratic input:         J3X=K3'*Q3*Q3*JR
dQ3=J3X-K4*Q3

JR=J0-J1-K2'*J2-K3'*J3-J1X-K2'*J2X-K3'*J3X
```


Energy
source
J_Q
J_R
X
J_3
Q
X
J_2
J_1
$K_4 * Q$
X
Q3
X
J_3X
$K_4 * Q_3$
Q2
X
J_2X
$K_4 * Q_2$
J_1X
Q1
$K_4 * Q_1$

For any system to survive over the long term, it must fit into a regime of disturbances or catastrophic events from sources outside its own boundaries. The system must be tuned to the frequencies of those systems that influence it in order to maximize power and survive. The three path model was simulated with various frequencies of power input to see how the various pathways process power at different frequencies and amplitudes.

Parallel production-consumption minimodel

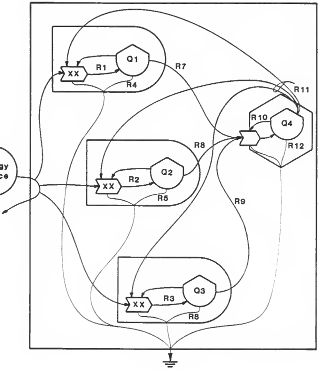
A model with producers in parallel was used to study the effects of competition among producers (Figure 13). The model had three producers, all having the same structure, with one aggregate consumer that was consuming all three and feeding back as a multiplier on the production function of each. It is a basic predator-prey model with competition among the different producers, along with feedback control and energy constraints in the form of a flow limited source. Instead of having combinations of pathways that can vary, this model had combinations of producers that could vary.

The producers had different turnover times and coefficients so that Q1, Q2, and Q3 represented climax, mid-successional (shrub) and early successional (weed) species. The coefficient of consumption (the percent of each producer the consumer eats per unit time) for each producer was different. The weed species had a higher value than the shrub species, which was higher than the climax species

Figure 13. Parallel production-consumption model.

```
Individual rate equations
     R1 = K1*Q1*JR*Q4
     R2 = K2*Q2*JR*Q4
     R3 = K3*Q3*JR*Q4
     R4 = D1*Q1
     R5 = D2*Q2
     R6 = D3*Q3
     R7 = K7*Q1*Q4
     R8 = K8*Q2*Q4
     R9 = K9*Q3*Q4
     R10 = F1*(K1*Q1*JR*Q4 + K2*Q2*JR*Q4 + K3*Q3*JR*Q)
     R11 = K0*(K7*Q1*Q4 + K8*Q2*Q4 + K9*Q3*Q4)
     R12 = D4*Q4
     JR  = J0/(1 + L1*Q1*Q4 + L2*Q2*Q4 + L3*Q3*Q4)

Rate equations for state variables
     dQ1 = R1 - R4 - R7
     dQ2 = R2 - R5 - R8
     dQ3 = R3 - R6 - R9
     dQ4 = R11 - R12 - R10
```


Energy source
Q1
R1
R4
R7
XX
R11
R10
Q4
R12
R8
Q2
XX
R2
R5
R9
Q3
XX
R3
R6

(Odum 1969). A list of coefficients is given in Appendix Table 3.

Several variations of this basic model were written in FORTRAN and BASIC computer languages and simulated on both a PDP 11/34 and on a Heathkit H8. The source listing for the standard parallel production-consumption model (SUC10) is presented in the Appendix.

Pulse Model

A general pulsing ecosystem model (Figure 14) was designed to test various hypotheses about energy flows and pulsing, hierarchical organization, and spatial development of ecosystems. Some of the structure of the model was derived after the tests of the threepath model and the parallel production-consumption model. The model had many characteristics of ecosystems such as:

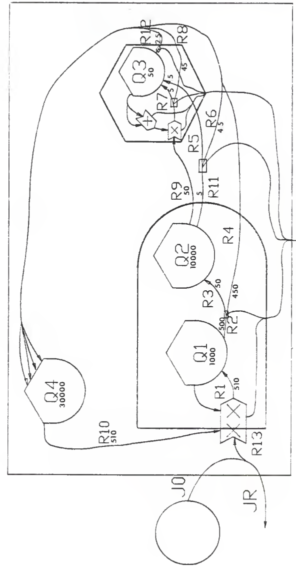
1. Flow limited resources (representing solar based energy resources).
2. Nutrient storage within the boundaries of the model.
3. Units of production, consumption and storage.
4. Feedback of consumers on production through nutrient recycle.
5. Consumption at low maintenance rates and at high pulsing rates.
6. Production through a fast turnover storage into a long turnover biomass storage.

The basic pulsing ecosystem model was tested for different flow rates, initial storages and energy inputs. From this, a baseline understanding of the dynamic behavior of the model and energy processing capabilities (as percent power used) was developed.

The pulse model (Figure 14) was similar to the one in Richardson and Odum (1981) with some changes in coefficients

Figure 14. Pulse model of tropical forest ecosystem model.

```
Individual rate equations:          Rate equations for state variables:
     R1 = K1*Q1*Q4*JR                    dQ1 = R1 - R2
     R2 = K2*Q1                          dQ2 = R3 - R9 - R11
     R3 = K3*Q1                          dQ3 = R7 + R5 - R12
     R4 = K4*Q1                          dQ4 = R12 + R8 + R6 - R10 + R4
     R5 = K5*Q2                          JR  = J0/(1 + K13*Q1*Q4)
     R6 = K6*Q2
     R7 = K7*Q2*Q3*Q3
     R8 = K8*Q2*Q3*Q3
     R9 = K9*Q2*Q3*Q3
     R10 = K10*Q1*Q4*JR
     R11 = K11*Q2
     R12 = K12*Q3
     R13 = K13*Q1*Q4*JR
```


Q1
1000
Q2
10000
Q3
50
Q4
30000
R1
510
R2
450
500
R3
50
R4
R5
R6
45
R7
5
R8
45
R9
50
R10
510
R11
5
R12
R13
J0
JR

and flows to calibrate it to a tropical rain forest ecosystem. The original model was run on an Electronics Associates Incorporated model 2000 Analog/Hybrid computer. The models presented in this dissertation were simulated on a DEC PDP 11/34. The multiple simulations of the pulse model were generated with a version of the program that would run 25 simulations while varying a coefficient or initial condition over those 25 runs and generate data files that were then displayed with the FORTRAN program PLOTZ (See Appendix). The source listing of the FORTRAN pulse program is in the Appendix.

The pulse model was calibrated with tropical forest ecosystem values for carbon flows and storages (Jordan and Drewry 1969, Odum and Pigeon 1970, and Brown, Lugo, Silander and Liegel 1983). The energy diagram of the model is given in Figure 14 and the equations, coefficients and initial conditions of the state variables are given in Appendix Table 4.

Pulse Model With Prey-Predator Sectors

An additional higher trophic level consumer was added to the pulsing consumer model (Figure 14) in order to test the relationship of turnover time and hierarchical matching of consumers (Figure 15). The extra consumer added to the model had the same structure as the lower level pulsing consumer (Q3), with both linear and quadratic pathways. This model was tested by varying the turnover time of the

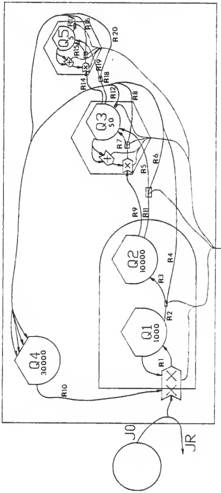
Figure 15. Pulse model with additional prey-predator sector.

Individual rate equations:

```
R1 = K1*Q1*Q4*JR
R2 = K2*Q1
R3 = K3*Q1
R4 = K4*Q1
R5 = K5*Q2
R6 = K6*Q2
R7 = K7*Q2*Q3*Q3
R8 = K8*Q2*Q3*Q3
R9 = K9*Q2*Q3*Q3
R10 = K10*Q1*Q4*JR
R11 = K11*Q2
R12 = K12*Q3
R13 = K13*Q1*Q4*JR
R14 = K14*Q3*Q5*Q5
R15 = K15*Q3*Q5*Q5
R16 = K16*Q3*Q5*Q5
R17 = K17*Q5
R18 = K18*Q3
R19 = K19*Q3
R20 = K20*Q3
```

Rate equations for state variables:

```
dQ1 = R1 - R2
dQ2 = R3 - R9 - R11
dQ3 = R7 + R5 - R12 - R18 - R14
dQ4 = R4 + R6 + R12 + R12 - R10
      + R16 + R17 + R20
dQ5 = R15 - R17 + R19
JR  = J0/(1 + K13*Q1*Q4)
```



Q1
1000
Q2
10000
Q3
50
Q4
30000
Q5
5
R1
R2
R3
R4
R5
R6
R7
R8
R9
R10
R11
R12
R14
R15
R16
R17
R18
R19
R20
J0
JR

highest level consumer (Q5) and measuring the percent power used and the level of the other storages in the system.

Spatial Models

The models previously discussed were time domain models with no spatial effects. However, because ecosystems develop through time and space and spatial variations can be at least as important as variations in time, spatial models were developed and simulated to test hypotheses concerning spatial development of ecosystems such as energy processing and pattern formation and hierarchical control of pattern formation.

The basic spatial model was a collection of subunits, each one a pulsing consumer model (Figure 14). These subunits were organized in a spatial format. When this simple model was simulated in a spatial format, size effects, edge effects and the consumer range of influence can become important. Intercell interactions between individual producers, consumers, nutrients, and energy sources may be important in energy utilization and pattern formation.

Effects of edges in the spatial model were of interest in pattern formation and energy use. Special boundary conditions were defined for the model cells along the edge. These boundary cells were manipulated in the simulation model in order to study the effects of edges on energy use and pattern formation. The boundary cells were also manipulated to minimize the effect of edges in certain runs of the model.

Any ecosystem can be divided into edge and non-edge (center) parts. The amount of edge in an ecosystem is a function of the size and number of the individual patches within it. For a given area, as the number of subunits increases the percent of the subunits on the edge decreases (see Figure 16).

A 10x10 matrix was used in the spatial simulations, giving 36% of the total in edge cells and 64% in non-edge cells. This size model was chosen to reduce the edge and yet be small enough to simulate in a reasonable time. Computer runs for this model lasted approximately 3 hours on a PDP 11/34. A model with a center to edge ratio of 10:1 would need approximately 20 times as many cells. In order to test the effects of edges on the model, a single layer of cells was added around the outside edges of the 10x10 matrix, giving it a 12x12 total area (Figure 17). The outer layer was not acted as a buffer to approximate conditions of an edgeless system.

Arrangements of cells

In simulating a spatial model, many arrangements of cells can be used. The simplest form used was a linear array with cells arranged in a linear ring. For two dimensional models the cell geometry chosen was a square. This was done for several reasons:

Figure 16. Number of edge and center cells as a function of total number of cells in a given square area.

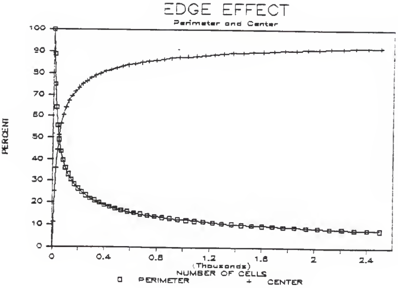
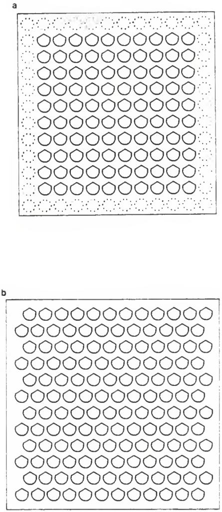

EDGE EFFECT
Perimeter and Center
PERCENT
100
90
80
70
60
50
40
30
20
10
0
0
0.4
0.8
1.2
1.6
2
2.4
(Thousands)
NUMBER OF CELLS
PERIMETER
CENTER

Figure 17. Cell geometries considered for spatial models.

(a) Square matrix with each cell having 4 side and 4 corner neighbors. Active 10x10 matrix embedded in a 12x12 matrix. This one was chosen for the spatial simulations.

(b) Hexagonal matrix with each cell having 6 side neighbors.



1. It simplified programming the model because two dimensional arrays in FORTRAN are set up in rows and columns.
2. It simplified writing the graphics routines to display the cells on a graphics terminal.
3. It reduced the edge effects of the model.

Ring model

A modified version of the two dimensional spatial model was used to simulate a one dimensional case. The standard spatial pulse model was connected head to tail in a ring of 36 cells.

Two dimensional models

The simplest spatial implementation was the basic pulse model repeated over the 10x10 matrix with no interactions between individual cells. This model (program DSP1) was then simulated with three different energy forcing functions:

1. The energy source was hierarchically distributed (highest energy input at the center of the matrix).
2. The energy source was evenly distributed.
3. The energy source was randomly distributed.

Energy inputs were scaled so the mean input over the whole matrix could be held constant for all energy types. Overall energy input could be varied to test pattern development and energy use with various energy levels.

Two different initial conditions were tested. A successional sequence was simulated with the initial values of

stored production (biomass, Q2 in Figure 14) set to a low level. A steady state configuration was also used in which Q2 was set to a value just below the pulse threshold. The nutrient tank (Q4) in each case was balanced to contain the remainder of carbon available in each cell.

This model tested different conditions and inputs.

1. Diffusion was allowed between nutrient tanks (Q4) of each subunit. The base model (DSP1) allowed nutrients to diffuse between cells at various diffusion rates. The outer layer of non-reacting cells (see Figure 17) had constant values for Q4 to allow tests of total diffusion into and out of the cell matrix (diffusion along the edges).

2. Diffusion was allowed between consumer tanks (Q3) of each subunit (program DSP1Q3). The outer non-reacting cell layer was set to a constant value or was allowed to float (program DSP1QZ) at the average of the inner 10x10 matrix to simulate a continuous sheet.

Simulations were run in which the consumer had a larger area or territory than the producer. A model variation (program DSP1C) was tested in which all of the consumer tanks were clumped into one tank that aggregated consumption over the 10x10 matrix simultaneously. This version also had three different input energy patterns available, and allowed diffusion between nutrient (Q4) tanks.

The final variation was a model with production compartmentalized as before in individual cells but with free roaming consumers, not constrained by cell boundaries. One consumer was allowed to consume and move about the matrix according to a set of constraints. When the consumer grew above a preset size, it was split into two equal halves and each half was allowed to consume, move and split again. An upper limit of 100 was placed on the total number of consumers that could be generated during the run (the total in the 10x10 matrix of the previous model versions). This model also had three different energy inputs and diffusion of nutrients (Q4).

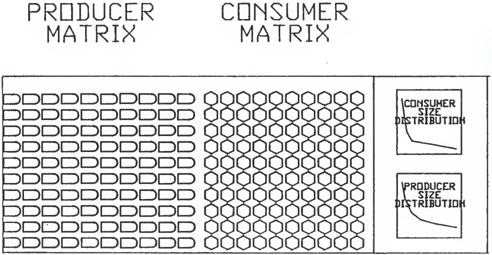
Format for Spatial Display Graphs

Data from the spatial pulsing model were displayed using the format shown in Figure 18. The spatial distributions of the producers and consumers were shown at various times during the run (usually 50 years apart). The values of producers and consumers in individual cells were represented by the density of dots in the cell. The producer density increment was 2000 g/m^2 with a range of 0-16,000 g/m^2 while the consumer was represented by an increment of 50 g/m^2 and a range of 0-400 g/m^2.

Measurement of Hierarchies at El Verde Site

In order to compare hierarchical relationships that were generated in the model with those occurring in the

Figure 18. Format of spatial model display graphs.


PRODUCER
MATRIX
CONSUMER
MATRIX
CONSUMER
SIZE
DISTRIBUTION
PRODUCER
SIZE
DISTRIBUTION

tropical rain forest at El Verde, several measurements were made from data sets from the tropical rain forest study at El Verde (1963-1967) in the Luquillo Mountains of Puerto Rico (Odum and Pigeon 1970).

A data set (2048 samples) characterizing the forest at the radiation site was generated by the U. S. Army Corps of Engineers (Rushing 1970). At the radiation site, every plant 1.8 m. or taller was enumerated within a radius of 30 m. from the center of the site. Each plant was recorded with the species name, height, diameter, crown diameter, exact location, and various other parameters.

Black and white negatives of aerial views of the radiation site (taken November 1963 before the radiation treatment) were printed as 8x10 inch photographs. Individual gaps characterized by the presence of *Cecropia peltata* (an early successional species) were digitized from the photographs using a personal computer, Complot digitizer and digitizing program written especially for this purpose (Measure3 in Appendix).

CHAPTER 3

RESULTS

Simulation of Three Path Model

Individual Pathway Tests

The amount of energy flowing through each of the pathways in the three path model (Figure 10) depends on the total energy input to the model. As input power (J0) was increased (Figure 19) steady state flows for each of the pathways changed. Each pathway predominates at certain times. The linear path had the largest power flow when input power was low, while the quadratic pathway had the highest flow at higher power inputs.

When input power was increased through time (Figure 20), there was no steady state, but, like Figure 19 when power increased, the energy flow shifted from the linear pathway to the autocatalytic and finally to the quadratic path. The fraction of energy remaining (Jr/J0) also decreased over time. As input power increased, a greater fraction of the input power was utilized.

The model was run with different pathway combinations (Figure 21) and with various power inputs. Each curve on the graph represents a steady state value for various combinations of pathways present in the simulation. Power used

Figure 19. Steady state power utilization of units in the three path model (Figure 10) as a function of input power (J0).

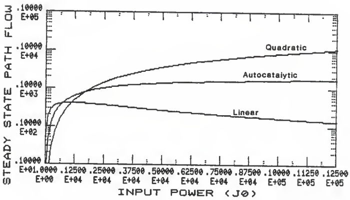

STEADY STATE PATH FLOW
.10000 E+05
.10000 E+04
.10000 E+03
.10000 E+02
.10000 E+01
.0000 E+00
.12500 E+04
.25000 E+04
.37500 E+04
.50000 E+04
.62500 E+04
.75000 E+04
.87500 E+04
.10000 E+05
.11250 E+05
.12500 E+05
Quadratic
Autocatalytic
Linear
INPUT POWER (J0)

Figure 20. Energy utilization of individual components in the three path model in Figure 10. Input power is increasing through time.

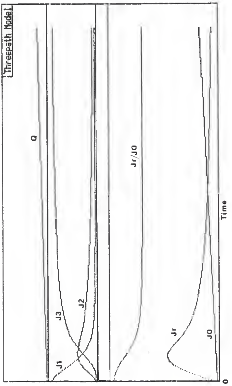
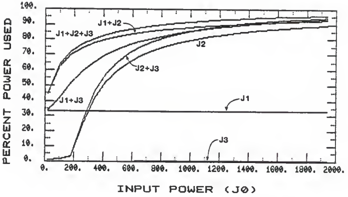

Threepath Model
Q
J1
J2
J3
Jr/J0
Jr
J0
Time
0

Figure 21. Steady state energy flows on various pathways and combinations of pathways in the three path model (Figure 10) as a function of input power (J0).

Linear pathway:	J1=K1*R
Autocatalytic pathway:	J2=K2*Q*R
Quadratic pathway:	J3=K3*Q*Q*R



100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
0.
PERCENT POWER USED
J1+J2
J1+J2+J3
J2
J2+J3
J1+J3
J1
J3
0.
200.
400.
600.
800.
1000.
1200.
1400.
1600.
1800.
2000.
INPUT POWER (J0)

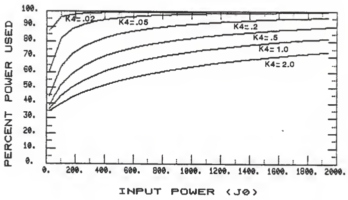
at any given input was highest with all three pathways present. For any combination of pathways that contained the quadratic path (J1+J2+J3 or J2+J3 or J1+J3), power used increased with power input to reach the same asymptote (>95% power used). A slightly lower level was reached for pathways dominated by the autocatalytic pathway (J2 or J2+J1). This asymptote was approximately 90% power used with increasing power input. With only the linear pathway enabled, no change occurred in percent power used with increasing power.

A unique situation occurred when the quadratic pathway (J3) existed alone. A low initial storage (Q) did not provide enough feedback on the J3 pathway to allow growth. Percent power used was never significant. The simulation with only J2 and J2+J3 showed zero percent power used at low input levels, then rose quickly at higher input power.

The size of the storage (Q) was varied to see the effects on energy usage (Figure 22). This was achieved by varying the depreciation coefficient (K4) in multiple run while increasing power input in the three path model. At high values of K4 (fast turnover times), increases in percent power used at steady state with increasing power were small. With decreasing values of K4 (slower turnover times), percent power used increased for the initial and final values of input power.

The addition of multiple drains with different structures (Figure 11) did not have as great an effect on the

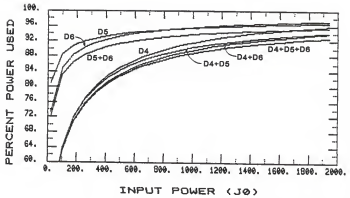
Figure 22 Simulation of three path model in Figure 10. Percent power used as a function of energy input and size of drain coefficient (K4 varied from .02 to 2.0).



PERCENT POWER USED
INPUT POWER (J0)
K4=.02
K4=.05
K4=.2
K4=.5
K4=1.0
K4=2.0
0.
10.
20.
30.
40.
50.
60.
70.
80.
90.
100.
0.
200.
400.
600.
800.
1000.
1200.
1400.
1600.
1800.
2000.

Figure 23. Simulation of three path model with multiple drain pathways in Figure 11. Percent power used as a function of energy input (J0).

Linear drain:	D4=k4*Q
Autocatalytic drain:	D5=K5*Q*Q
Quadratic drain:	D6=K6*Q*Q*Q

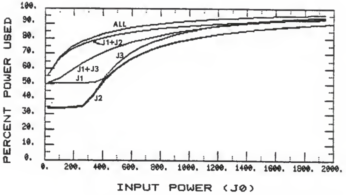

PERCENT POWER USED
100.
96.
92.
88.
84.
80.
76.
72.
68.
64.
60.
0.
200.
400.
600.
800.
1000.
1200.
1400.
1600.
1800.
2000.
INPUT POWER (J0)
D6
D5
D5+D6
D4
D4+D5
D4+D6
D4+D5+D6

model as multiple inflow pathways. The percent power used was lowest when all combinations of drain pathways were enabled (Figure 23). Percent power used increased with increasing input power. The highest value for percent power used was achieved when only the original linear drain was present. Any combination with the linear drain used less power at low power inputs than the nonlinear pathways alone or in combination. The higher order drains enabled the system to draw more power at low levels than when combined with linear pathways. This effect was opposite from that with input pathways at very low power where the nonlinear pathways did not function well (see Figure 21).

The effects of adding competition pathways to the model (Figure 12) can be seen in Figure 24. In this case, each of the competing pathways (single tanks Q1, Q2, and Q3 with individual pathways) were left on throughout the simulations. Here again the various pathways were disabled and simulations run with varying power inputs. The results were similar in some ways to those in Figure 21 where at high power inputs the percent power used approached one of two asymptotes. The greatest percentage of power utilization occurred when all pathways were enabled and the lowest power utilization occurred when only J2 or J3 were enabled. The addition of the extra competing storages increased the percent power used in each of the pathway combinations compared to Figure 21. These extra pathways were always there to use

Figure 24. Simulation of three path competition model with various pathways enabled (Figure 12). Percent power used as a function of energy input (J0).

Linear pathway:	J1=K1*R
Autocatalytic pathway:	J2=K2*Q*R
Quadratic pathway:	J3=K3*Q*Q*R


PERCENT POWER USED
100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
0.
ALL
J1+J2
J3
J1+J3
J1
J2
0.
200.
400.
600.
800.
1000.
1200.
1400.
1600.
1800.
2000.
INPUT POWER (J0)

whatever power may be left over (particularly the linear path).

Frequency Studies

The basic three path model (Figure 10) was also used to test the effects of different frequencies of input power on the model at three different power levels. At the lowest power level (J0=500, Figure 25) the differences between pathways in percent power used was the greatest. The greatest frequency response occurred at low frequencies. The frequency response was flat with only the linear path enabled. When all pathways were present, the percent power used was highest with a peak at approximately 2 cycles. A peak of power utilization also occurred with the combinations of J1+J2 and J1+J3. The pathways that showed a minimum in the frequency response were composed of J2+J3 (the two nonlinear pathways combined) and J2. The quadratic pathway alone did nothing since no power was used (compare with Figure 21).

When the input power was increased to 2000 (Figure 26), the linear pathway showed no change in output with change in frequency and the quadratic pathway had no output. The combination of J1+J2 here again had a slight maximum at about 2 cycles while J2 alone had a maximum at zero cycles. The combination of all of the pathways (J1+J2+J3) and J1+J3 had a slight minimum of power utilization at about 8 cycles, while the combination of J2+J3 showed a slight minimum at about 2 cycles.

Figure 25. Simulation of the three path model in Figure 10. Percent power used as a function of frequency of the input power (J0=500).

Linear pathway:	J1=K1*R
Autocatalytic pathway:	J2=K2*Q*R
Quadratic pathway:	J3=K3*Q*Q*R

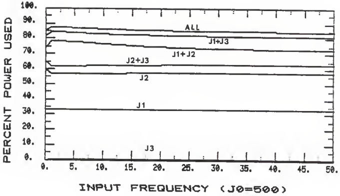
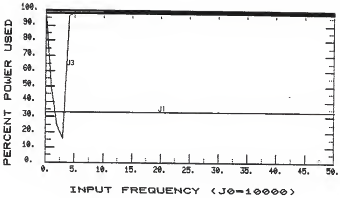

PERCENT POWER USED
100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
0.
ALL
J1+J3
J1+J2
J2+J3
J2
J1
J3
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
INPUT FREQUENCY (J0=500)

Figure 26. Simulation of the three path model in Figure 10. Percent power used as a function of frequency of the input power (J0=2000).

Linear pathway:	J1=K1*R
Autocatalytic pathway:	J2=K2*Q*R
Quadratic pathway:	J3=K3*Q*Q*R


PERCENT POWER USED
100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
0.
J3
J1
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
INPUT FREQUENCY (J0=10000)

When the input power was raised to 10000 (Figure 27) the percent power used went up for all combinations of pathways except the linear path. The quadratic pathway was operational at this high power level but with a significant minimum at 2 cycles per run. Other combinations had small minima and maxima that are hard to see at the scale of this graph.

The response of the model to various frequencies and power input is shown in Table 1. Simulation runs with pathway J1+J2 had a maximum in percent power used at all three power inputs while the combination of J2+J3 had a minimum in percent power used at all three power inputs. The combination of all pathways (J1+J2+J3) has a peak of maximum percent power utilization at low power and low frequency input. At higher power levels percent power utilization (with all three pathways enabled) was lower with some shifting in the frequency at which this occurs.

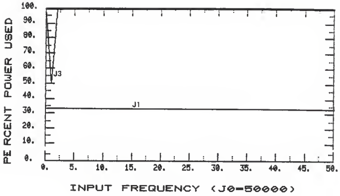
Simulation of Parallel Production-Consumption Model

Single Run Simulations

The parallel production model showed a successional pattern with the initial dominant species (Q3, with the fastest turnover) growing up, then declining as Q2 became the dominant species and finally Q1 (with the slowest turnover) reached a maximum and then dropped back to a slightly lower steady state (Figure 28). The consumer (Q4, with the

Figure 27. Simulation of the three path model in Figure 10. Percent power used as a function of frequency of the input power (J0=10000).

Linear pathway:	J1=K1*R
Autocatalytic pathway:	J2=K2*Q*R
Quadratic pathway:	J3=K3*Q*Q*R



PERCENT POWER USED
100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
0.
J3
J1
0.
5.
10.
15.
20.
25.
30.
35.
40.
45.
50.
INPUT FREQUENCY (J0=50000)

Table 1. Frequency response (minimums and maximums) of three path model (Figure 10) with varying input power.

Pathway combination	INPUT POWER J0=500	J0=2000	J0=10000
J1+J2+J3 (All)	MAX (2)	MIN (8)	MIN (3)
J2+J3	MIN (2)	MIN (2)	MIN (2)
J1+J3	MAX (2)	MIN (8)	MIN (3)
J1+J2	MAX (2)	MAX (2)	MAX (2)
J1	N/R	N/R	N/R
J2	MIN (2)	MAX (0)	MAX (0)
J3	N/O	N/O	MIN (2)

Numbers in parenthesis are the frequencies at which the maximum or minimum occurs.

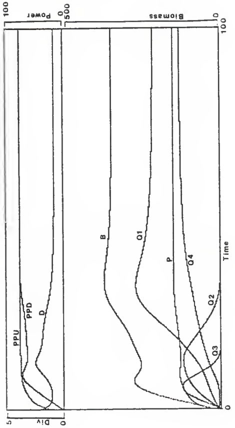
N/R signifies there was no frequency response for this set of pathways.

N/O signifies there was no power uses at these inputs

Figure 28. Simulation of the four sector succession model in Figure 13. Model base run.

Legend:

PPU = Percent power used
PPD = Percent power drained
D = Diversity
B = Total Biomass
P = Productivity
Q1 = Climax species
Q2 = Mid successional species
Q3 = Early successional species
Q4 = Consumer


100
Power
0
500
Biomass
0
100
PPU
PPD
D
B
Q1
P
Q4
Q2
Q3
Time
5
Div
0
0

longest turnover time per unit) also rose to a steady state value. During this time, the productivity climbed to a local maxima, then dropped slightly, finally climbing to a slightly higher steady state. The percent power used for the whole run was 95.5%.

In order to test the role of each of the producers early in the simulation, a series of runs were made with the initial condition of one of the producer species set to zero (Figure 29 a,b,c). With no initial climax species (Q1) present (Figure 29a) the shrub species (Q2) became dominant in the final steady state. The percent power used for the run was 94.7%, slightly less than the base run configuration. This configuration did not support as high a level of consumer (Q4) compared to the base model run (75.2 vs. 90.8).

When the shrub species (Q2) was absent (Figure 29b), the percent power used for the run and steady state values for the consumers were similar to the base run. Without the shrub species present to compete during the middle period, the final climax species (Q1) peaked earlier and higher than in the base run.

When the weed species (Q3) was initially absent (Figure 29c), the system was not self sustaining. The primary reason was that during the early part of the simulation, the consumer (Q4) was dependent on the weed species (Q3). With no Q3 present, the consumer crashed very quickly. The whole system then crashed because the consumer feeds back in

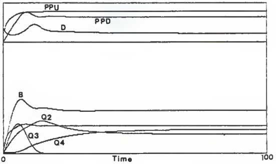
Figure 29 Simulation of the parallel production-consumption model in Figure 13. See Figure 28 for legend and ordinate scale.

(a) Simulation run with initial value of climax species (Q1) set equal to zero.

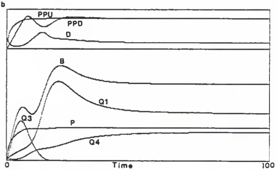
(b) Simulation run with initial value of intermediate species (Q2) set equal to zero.

(c) Simulation run with initial value of weed species (Q3) set equal to zero.

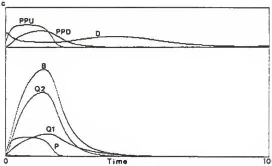
a


PPU
PPD
D
B
Q2
Q3
Q4
0
Time
100

b


PPU
PPD
D
B
Q1
Q3
P
Q4
0
Time
100

c


PPU
PPD
D
B
Q2
Q1
P
0
Time
100

the production function of all of the producers in the system.

When the model was simulated with no initial consumer (Q4), it crashed even faster (not shown) than in Figure 29c because of the feedbacks in the model from the consumer to the producers.

Multiple Run Simulations

The behavior of the parallel production model with varying input power is seen in Figure 30a-f. In this set of runs the base model was run for 100 time units. For each successive run, the input power (J0) was increased, varying from 50 to 300. As the energy input increased, the peaks of the producers were higher (Q1-Q3), with Q3 (the weed species) showing the most change in amplitude (Figure 30c). The climax species (Q1) peaked sooner as the input power increased.

The simulation of succession to a climax was thus speeded up by increasing the energy input at lower levels, but at higher levels the increase in energy had little effect on the transition to dominance of the climax species.

The effect of increasing energy input was also seen in the level of the consumer (Q4 in Figure 30d). With increasing power, the consumer was maintained at a proportionately higher steady state.

For this set of simulations, as the input power increased, the percent power used increased asymptotically (Figure 31). There was a diminishing return on the input

Figure 30. Simulation of the parallel production-consumption model in Figure 13. Multiple simulations of the model with available power increasing from 50 to 300.

(a) Climax species (Q1)
(b) Intermediate producer species (Q2)
(c) Weed species (Q3)
(d) Consumer species (Q4)
(e) Percent power used (J0-Jr)/J0
(f) Total biomass

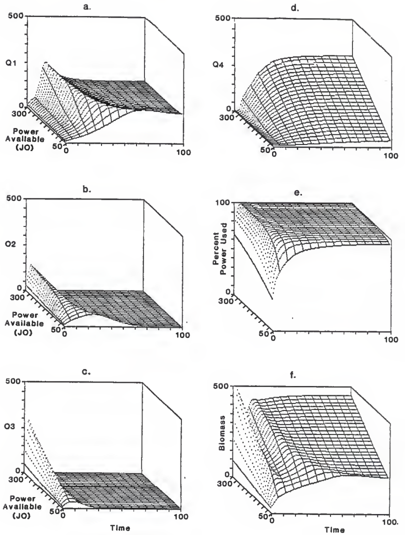
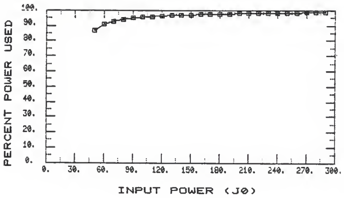
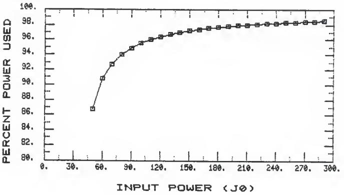

a.
500
Q1
0
300
Power Available (JO)
50
0
100
b.
500
O2
0
300
Power Available (JO)
50
0
100
c.
500
O3
0
300
Power Available (JO)
50
0
100
Time
d.
500
Q4
0
300
50
0
100
e.
100
Percent Power Used
0
300
50
0
100
f.
500
Biomass
0
300
50
0
100.
Time

Figure 31. Simulation of the parallel production-consumption model in Figure 13. Multiple simulations of the model with percent power used for entire run vs input power. See Figure RS3a-f.


PERCENT POWER USED
100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
0.
0. 30. 60. 90. 120. 150. 180. 210. 240. 270. 300.
INPUT POWER (J0)


PERCENT POWER USED
100.
98.
96.
94.
92.
90.
88.
86.
84.
82.
80.
0. 30. 60. 90. 120. 150. 180. 210. 240. 270. 300.
INPUT POWER (J0)

power as the effect was greater at low power than it was at higher levels of power.

When the input power was varied as in the previous example (50 to 300) but the initial condition of the consumer was started at a higher level (Q4INIT=50, 10x base run value) the results were similar to the previous run but damped (Figure 32a-f). The shift in time of the peak of the climax species (Q1) was less than before and the amplitudes of the initial peaks of Q2 and Q3 were less. Percent power used per time increment also was higher in the earlier stages of this run compared to the previous run (compare Figure 32e with 30e). With higher initial levels of the consumer, the model generated more power earlier through the feedback of the consumer on the producers.

When the input power was held constant (J0=100) and the initial condition of the consumer (Q4) varied, the model displayed two different behaviors (Figure 33a-f). With few consumers initially, the system crashed, unable to proceed through the normal growth sequence. When the initial quantity of the consumers (Q4) was above a critical level, the system grew and went through a normal growth sequence. A sharp transition occurred in the percent power used as Q4INIT was increased (Figure 34).

Because the consumer (Q4) was feeding back as a multiplier to the producers, some minimum critical value must exist for the consumer population to stabilize this model.

Figure 32. Simulation of the parallel production-consumption model in Figure 13. Run with available power increasing from 50 to 300 and the initial value of the consumer (Q4) equal to 50 (10x base run in Figure 28).

(a) Climax species (Q1)
(b) Intermediate producer species (Q2)
(c) Weed species (Q3)
(d) Consumer species (Q4)
(e) Percent power used (J0-Jr)/J0
(f) Total biomass

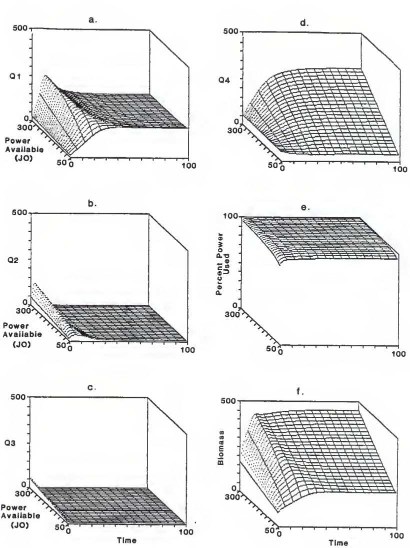

a.
500
Q1
0
300
Power
Available
(JO)
50
0
100
b.
500
Q2
0
300
Power
Available
(JO)
50
0
100
c.
500
Q3
0
300
Power
Available
(JO)
50
0
Time
100
d.
500
Q4
0
300
50
0
100
e.
100
Percent Power
Used
0
300
50
0
100
f.
500
Biomass
0
300
50
0
Time
100

Figure 33. Simulation of the parallel production-consumption model in Figure 13. Multiple simulations of the model with available power held constant (J0=100, base run value) and the initial value of the consumer (Q4) varied from 1 to 6.

(a) Climax species (Q1)
(b) Intermediate producer species (Q2)
(c) Weed species (Q3)
(d) Consumer species (Q4)
(e) Percent power used (J0-Jr)/J0
(f) Total biomass

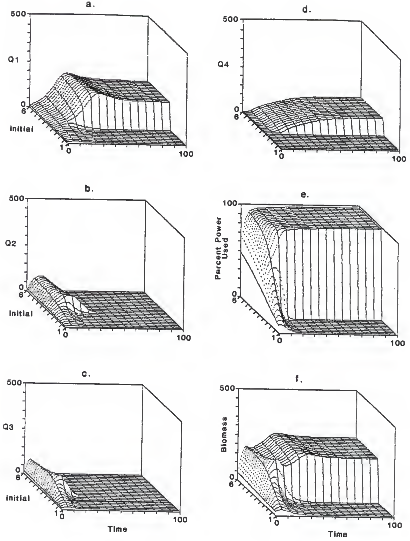
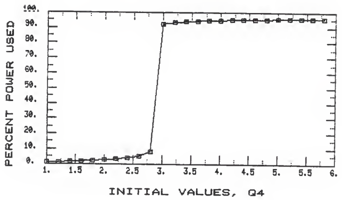

a.
500
Q1
0
6
initial
1
0
100
d.
500
Q4
0
6
1
0
100
b.
500
Q2
0
6
Initial
1
0
100
e.
100
Percent Power Used
0
6
1
0
100
c.
500
Q3
0
6
Initial
1
0
100
Time
f.
500
Biomass
0
6
1
0
100
Time

Figure 34. Simulation of the parallel production-consumption model in Figure 13. Total percent power used for entire run as a function of the initial value of the consumer (Q4). This represents a cross section of Figure 33e.


PERCENT POWER USED
100.
90.
80.
70.
60.
50.
40.
30.
20.
10.
0.
1.
1.5
2.
2.5
3.
3.5
4.
4.5
5.
5.5
6.
INITIAL VALUES, Q4

Either immigration or a temporary auxiliary support system is necessary to start a system of this class.

Similarly, when the input power was held constant (J0=100) and the initial condition of the weed species (Q3) was varied (Figure 35a-f), the system crashed at low levels of Q3, but at higher levels it was stable (see Figure 29c for a single run with Q3=0).

The system response was different with changes in the initial conditions of Q1 and Q2 (refer to Figures 29a and 29b) because the consumer was not as dependent upon them for its survival early in the simulation.

Initial Conditions and Total Energy Use

The behavior of the parallel production-consumption model with different initial conditions for the state variables (Q1, Q2, Q3, and Q4) and input power was tested. In this set of simulations, the total percent power used was measured for each simulation run while varying the input power and the initial condition of the state variables one at a time (Figure 36).

In all four cases when J0 was low, the model was unable to utilize the energy available to it. When the input power was above a certain point then the model was able to utilize the input energy with two exceptions. When Q3 (weed species) was very low, the percent power used rose to a plateau then fell when the input energy went above a certain level. The model was unstable under these conditions.

Figure 35. Simulation of the parallel production-consumption model in Figure 13. The initial value of weed species (Q3) was varied from 0 to .5 and input power was held constant (J0=100, base run value).

(a) Climax species (Q1)
(b) Intermediate producer species (Q2)
(c) Weed species (Q3)
(d) Consumer species (Q4)
(e) Percent power used (J0-Jr)/J0
(f) Total biomass

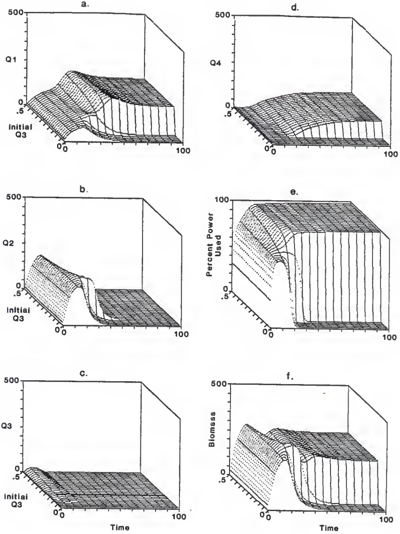
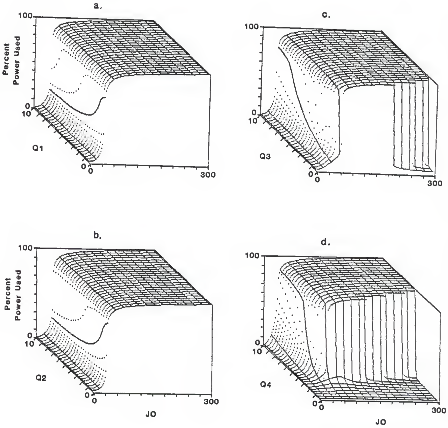

a.
500
Q1
0
.5
Initial
Q3
0
0
100
d.
500
Q4
0
.5
0
0
100
b.
500
Q2
0
.5
Initial
Q3
0
0
100
e.
100
Percent Power
Used
0
.5
0
0
100
c.
500
Q3
0
.5
Initial
Q3
0
0
100
Time
f.
500
Biomass
0
.5
0
0
100
Time

Figure 36. Steady state values of percent power used as a function of input energy and state variable initial conditions for multiple simulation runs of parallel production-consumption model (Figure 13).

(a) Vary input energy and Q1 (Climax species)
(b) Vary input energy and Q2 (Intermediate producer)
(c) Vary input energy and Q3 (Weed Species)
(d) Vary input energy and Q4 (Consumer)


a.
100
Percent Power Used
0
10
Q1
0
0
300
c.
100
0
10
Q3
0
0
300
b.
100
Percent Power Used
0
10
Q2
0
0
300
JO
d.
100
0
10
Q4
0
0
300
JO

When Q4 was below a certain threshold the system could not be sustained regardless of the input energy. After an initial threshold level of consumers was reached, the system was stable, similar to that described above for Q3. Since Q4 has a direct feedback on Q1, Q2, and Q3, the interaction of these in the production term can determine whether or not the system was stable. If the value of Q4 was too low then there was little production and the system crashed.

Simulation of the Pulse model

Single Run Simulations

A simulation of the base run pulse model (Figure 14) is shown in Figure 37a. As Q2 increased, the available carbon or nutrient carbon tank (Q4) decreased proportionately. As the stored biomass increased there was a threshold level at which the consumer (Q3) began to grow rapidly and pulsed. This pulse consumed Q2 and released the carbon back into the available carbon pool (Q4). The threshold of pulsing was dependent on the level of both Q2 and Q3. The level of Q3 before the pulse was, however. directly related to the level of Q2 and the input diffusion pathway. After the pulse, the consumer (Q3) decayed back to a low level.

The cycle repeats itself at a frequency of approximately 325 years. The power used varied during the simulation with the highest rate occurring shortly after the pulse, when the nutrients have been concentrated in Q4 as available carbon.

Figure 37. Simulation for pulse model (Figure 14) with base run coefficients (See Appendix).

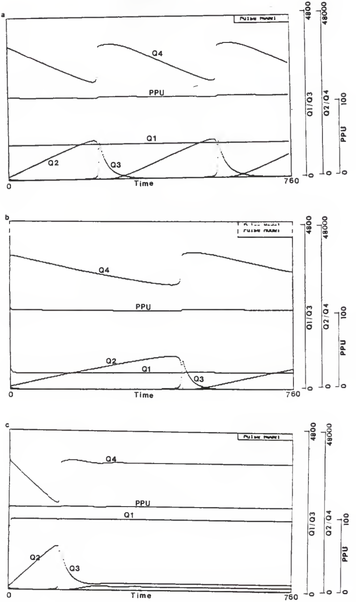
(a) Base run of model.

(b) Input energy one-half of base run.

(c) Input energy two times the base run.

Legend:

PPU = Percent power used
Q1 = Production unit
Q2 = Stored biomass
Q3 = Pulse consumer
Q4 = Nutrient storage


a
Q4
PPU
Q1
Q2
Q3
0
Time
760
Q1/Q3
4800
0
Q2/Q4
48000
0
PPU
100
0
b
Q4
PPU
Q2
Q1
Q3
0
Time
760
c
Q4
PPU
Q1
Q2
Q3
0
Time
760

If the input energy was less (J0=50, half of the base run) then the pulse came at a later time (Figure 37b) and the frequency of pulsing had a longer period. The production was lower and the stored biomass (Q2) took longer to reach the level that would trigger the pulse in the consumer (Q3).

When the input energy was raised to twice the level of the base run (J0=200), the consumer pulsed only one time (Figure 37c) and then remained at a low level instead of decaying away entirely as in the base run. With a low level of consumer, the stored biomass was not able to build up and remained at a lower steady-state level.

The total power used for each of these runs was related to the input power. As the input power went up, the percent power used also went up from 93.3 at 50%, to 96.5 at 100% and 98.3 at 200%.

The quadratic pathway between the stored biomass (Q2) and the consumer (Q3) was responsible for the pulsing much as the autocatalytic pathway of a Lotka-Volterra model is responsible for its oscillating limit-cycle behavior. With only the linear path between Q2 and Q3, the behavior was not pulsing or oscillatory (Figure 38). The stored biomass grew while the nutrients were used up. In this time frame (760 years), the values did not reach a steady state and 93% of the available power was used. When simulated for 2000 time units (Figure 38b), the percent power used dropped off to a low steady state value. The system became nutrient limited

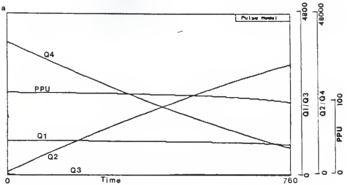
Figure 38. Simulation of pulse model (Figure 14) without a quadratic pathway (K7, K8, K9 = 0.0).

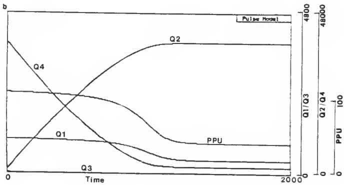
(a) Simulation for 760 years.

(b) Simulation for 2000 years.

Legend:

PPU = Percent power used
Q1 = Production unit
Q2 = Stored biomass
Q3 = Pulse consumer
Q4 = Nutrient storage


a
Pulse Model
Q4
PPU
Q1
Q2
Q3
0
Time
760
Q1/Q3
4800
0
Q2/Q4
48000
0
PPU
100
0


b
Pulse Model
Q2
Q4
Q1
PPU
Q3
0
Time
2000
Q1/Q3
4800
0
Q2/Q4
48000
0
PPU
100
0

because most of the nutrients were tied up in the stored biomass.

When the pulse model was run without feedbacks into Q4 (pathways R6 and R8 cut off) the model continued to pulse but began to decline (Figure 39). The percent power used dropped as the level of Q4 dropped until one final pulse and then everything decayed to a low steady state condition.

Multiple-run Simulations

When the input power was increased, the result was most noticeable on the stored biomass (Q2) and the consumer (Q3, Figure 40). At low values of J0 there was no pulsing within the time frame of the simulation (760 years). As J0 was increased, the pulsing began as a result of the stored biomass (Q2) increasing to a threshold level at which Q3 pulsed and consumed the stored biomass (Q2). As J0 was further increased, the pulsing frequency increased. At high levels of J0 the first pulse decayed and the system switched to a steady state with Q2 being maintained at a low level (see Figure 37c for example). The total power used (Figure 40e) increased linearly as J0 increased with small fluctuations over time due to the pulsing of Q3. The percent power used (Figure 40f) was less than 80% for low values of J0 then rose rapidly through the pulsing and leveled off as J0 approached 250. The percent power used was reduced by the initial consumption but returned to a maximum after the pulse. The percent power used increased as the available

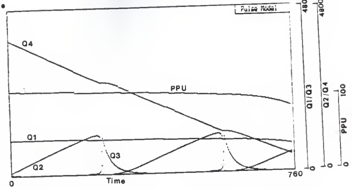
Figure 39. Simulation of pulse model (Figure 14) without feedbacks into Q4 (K6, K8 = 0.0)

(a) Simulation for 760 years.

(b) Simulation for 2000 years.

Legend:

PPU = Percent power used
Q1 = Production unit
Q2 = Stored biomass
Q3 = Pulse consumer
Q4 = Nutrient storage


Pulse Model
Q4
PPU
Q1
Q3
Q2
0
Time
760
4800
Q1/Q3
0
48000
Q2/Q4
0
100
PPU
0

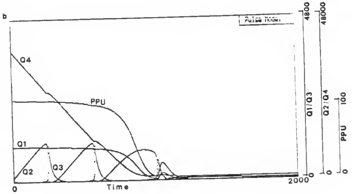
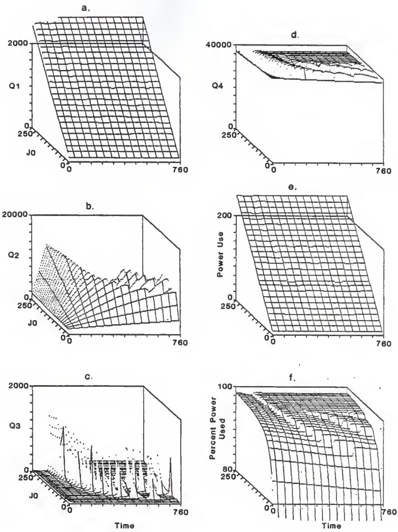

b
Pulse Model
Q4
PPU
Q1
Q2
Q3
0
Time
2000
4800
Q1/Q3
0
48000
Q2/Q4
0
100
PPU
0

Figure 40. Multi-run simulation of the pulse model (Figure 14) with variation in input energy. (J0 varied from 0 to 250).

(a) Production unit (Q1).
(b) Stored biomass (Q2).
(c) Pulse consumer (Q3).
(d) Nutrient storage (Q4).
(e) Power used (J0-Jr)
(f) Percent power used 100*(J0-Jr)/(J0)


a.
2000
Q1
0
250
J0
0
0
760
b.
20000
Q2
0
250
J0
0
0
760
c.
2000
Q3
0
250
J0
0
0
760
Time
d.
40000
Q4
0
250
0
0
760
e.
200
Power Use
0
250
0
0
760
f.
100
Percent Power Used
80
250
0
0
760
Time

power was increased (similar to three path models seen earlier) with local maxima immediately after the pulse.

The total amount of nutrients in the system also had an important effect on the behavior of the model (Figure 41a-f). At higher initial levels of Q4 there was little effect on the model. At these higher ranges, the model was no longer nutrient limited but was energy limited. At low values for the initial concentration of Q4 the pulsing greatly affected the labile production (Q1), the stored biomass (Q2) and the pulsing consumer (Q3). At the lowest level of Q4, there was no pulsing, Q2 remained at a low steady state value, and Q3 also remained at a low steady state value. There was a small shift in the pulsing frequency at the lowest initial levels of Q4 but no frequency shift at the higher levels. The power used was greatly affected at low initial levels of Q4 but rose only slightly at higher values of Q4. For the same amount of change in Q4, the variability of the power used was greater when Q4 was small than when Q4 was high. However, the percentage change was greater in the beginning than at the end.

The turnover time of the pulsing consumer affected the behavior of the system and use of power (Figure 42a-f). The pulse model was simulated with the value of the drain coefficient (K12) of the consumer (Q3) varied with each run. As the turnover time increased, the frequency of pulsing shifted to a shorter period with the amplitude decreasing until there is no pulse at all but a continually rising consumer.

Figure 41. Multi-run simulation of pulse model (Figure 14) with variation in total carbon in model. (Q4 varied from 2000 gC/m2 to 100,000 gC/m2.

(a) Production unit (Q1).
(b) Stored biomass (Q2).
(c) Pulse consumer (Q3).
(d) Nutrient storage (Q4).
(e) Power used (J0-Jr)
(f) Percent power used 100*(J0-Jr)/(J0)

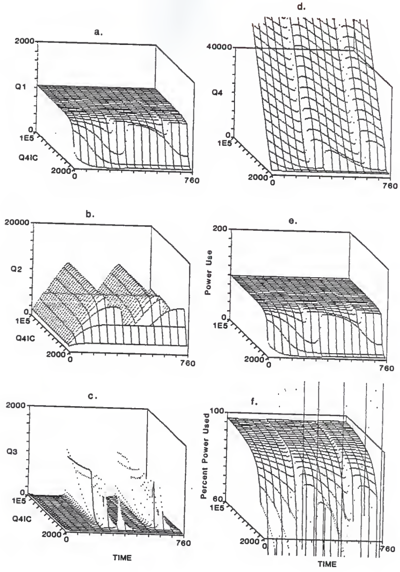
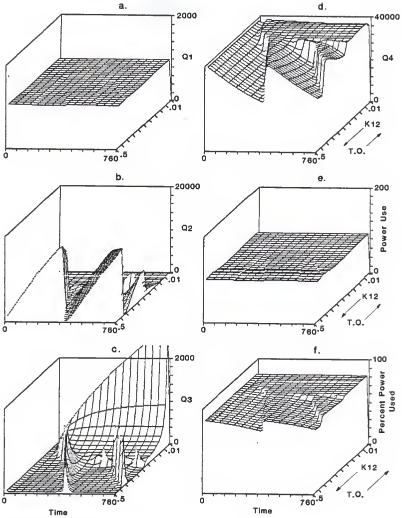

a.
2000
Q1
0
1E5
Q4IC
2000
0
760
b.
20000
Q2
0
1E5
Q4IC
2000
0
760
c.
2000
Q3
0
1E5
Q4IC
2000
0
760
TIME
d.
40000
Q4
0
1E5
2000
0
760
e.
200
Power Use
0
1E5
2000
0
760
f.
100
Percent Power Used
60
1E5
2000
0
760
TIME

Figure 42. Multi-run simulation of pulse model (Figure 14) with variation is turnover time of pulsing consumer. (K12 varied from .01 to .5).

(a) Production unit (Q1).
(b) Stored biomass (Q2).
(c) Pulse consumer (Q3).
(d) Nutrient storage (Q4).
(e) Power used (J0-Jr)
(f) Percent power used 100*(J0-Jr)/(J0)


a.
2000
Q1
0
.01
0
760
.5
b.
20000
Q2
0
.01
0
760
.5
c.
2000
Q3
0
.01
0
760
.5
Time
d.
40000
Q4
0
.01
K12
T.O.
0
760
.5
e.
200
Power Use
0
.01
K12
T.O.
0
760
.5
f.
100
Percent Power Used
0
.01
K12
T.O.
0
760
.5
Time

This implies there is a 'window' of size for the consumer to pulse.

Changing the rate constant (K9) of the quadratic pathway caused the pulsing consumer to change frequency, increasing the frequency of pulsing with an increasing coefficient value (Figure 43). There was a point in this set of simulations where the pulsing ceases but in this case the size of the consumer remains small. When the quadratic pathway became dominant at low consumer levels, the system did not pulse but completely consumed the stored biomass storage (Q2).

When simulated without the quadratic pathway and changing the coefficient of the linear pathway (K11), the model did not pulse, the consumer (Q3) remained at a low level and the stored biomass (Q2) built up (Figure 44, compare to single run Figure 38). As the linear pathway increased, there was a slight increase in the consumer (Q3) with less of a build-up in the stored biomass (Q2). In all cases, through time the power use and percent power used dropped off.

Simulation of Pulse Model with Prey-Predator Sectors

Simulation of the pulse model with an additional prey-predator sector (Figure 15) investigated how turnover time is related to hierarchical consumers (Figure 45). With a drain coefficient on Q5 the same as or larger than that of the normal pulsing consumer (K17=0.05 or 0.5), the effect

Figure 43. Multi-run simulation of pulse model (Figure 14) with variation in quadratic pathway (K9 varied from 0.5E-6 to 0.53E-5 with K7 and K8 varied proportionately).

(a) Production unit (Q1).
(b) Stored biomass (Q2).
(c) Pulse consumer (Q3).
(d) Nutrient storage (Q4).
(e) Power used (J0-Jr)
(f) Percent power used 100*(J0-Jr)/(J0)

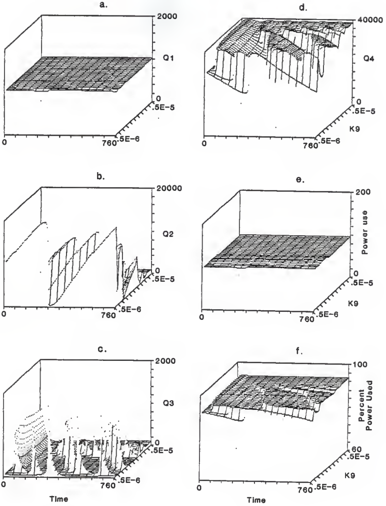

a.
2000
Q1
0
.5E-5
.5E-6
0
760
b.
20000
Q2
0
.5E-5
.5E-6
0
760
c.
2000
Q3
0
.5E-5
.5E-6
0
760
Time
d.
40000
Q4
0
.5E-5
K9
.5E-6
0
760
e.
200
Power use
0
.5E-5
K9
.5E-6
0
760
f.
100
Percent
Power Used
60
.5E-5
K9
.5E-6
0
760
Time

Figure 44. Multi-run simulation of pulse model (Figure 14) with variation in linear pathway (K11 varied from 0.0 to 0.12E-2 and K5 and K6 varied proportionately) with quadratic pathway held at zero.

(a) Production unit (Q1).
(b) Stored biomass (Q2).
(c) Pulse consumer (Q3).
(d) Nutrient storage (Q4).
(e) Power used (J0-Jr)
(f) Percent power used 100*(J0-Jr)/(J0)

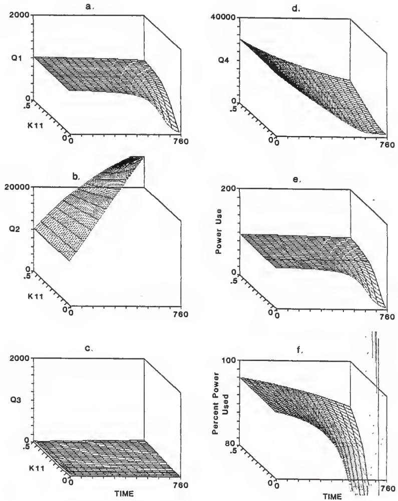
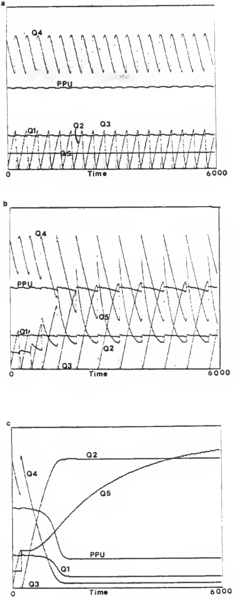

a.
2000
Q1
0
.5
K11
0
0
760
d.
40000
Q4
0
.5
0
0
760
b.
20000
Q2
0
.5
K11
0
0
760
e.
200
Power Use
0
.5
0
0
760
c.
2000
Q3
0
.5
K11
0
0
760
TIME
f.
100
Percent Power Used
80
.5
0
0
760
TIME

Figure 45. Simulation of pulse model with prey-predator sectors (Figure 15).

(a) Simulation with turn-over time of higher level pulsing consumer (Q5) set equal to lower level pulsing consumer (Q3).

(b) Simulation with turn-over time of higher level pulsing consumer (Q5) set to ten times longer than the turn-over time of lower level pulsing consumer (Q3).

(c) Simulation with turn-over time of higher level pulsing consumer (Q5) set to one hundred times longer than the turn-over time of the lower level puling consumer (Q3).


a
Q4
PPU
Q1
Q2
Q3
Q5
0
Time
6000
b
Q4
PPU
Q5
Q1
Q2
Q3
0
Time
6000
c
Q2
Q4
Q5
PPU
Q1
Q3
0
Time
6000

was hardly detectable in the simulation result (Figure 45a). The frequency of pulsing was not changed and the power utilized was only negligibly changed. The higher level consumer (Q5) was near zero for the entire simulation.

When the model was run with a turnover time (K17=0.005) of the top consumer (Q5) longer than the normal pulsing consumer (Figure 45b), pulsing occurred at the normal frequency but the higher level consumer grew over time until it began pulsing. The period of pulsing became longer and the pulse amplitude of the stored producer and nutrient storages became greater. The normal pulsing consumer (Q3) remained at a low level, acting as a feeder to the higher level consumer (Q5). The power utilized dropped slightly to 95.3.

When the turnover time of the higher level consumer (Q5) was raised by another order of magnitude (K17= 0.0005) the outcome was quite different (Figure 45c). The higher level pulsing consumer (Q5) climbed toward an asymptote while the stored production (Q2) also climbed to a steady state value. the normal pulsing consumer (Q3) again remained at a low level. In this case the nutrients (Q4) became tied up in the stored biomass (Q2) the power used dropped to 36.1 at steady state. The percent power used for the entire simulation was 48.2.

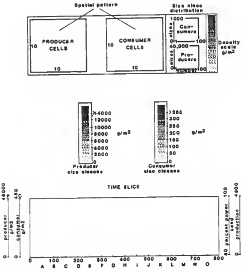
Simulation of the Ring Model

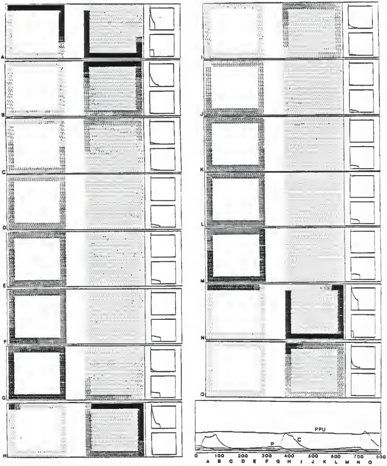
The linear array ring model was simulated with high diffusion (DK=.1) between consumers in adjacent cells (Figure 46). Initially the concentration of producers and consumers around the ring was constant except for a single consumer at a high level (Q3(2,2)=100.; lower left hand corner of consumer matrix). At T=50 years (Figure 46A), the consumers had pulsed in both directions around the ring and completely encircled the ring by T=100 (46B). At T=150 (46C), the production was beginning to spread around the ring from the lower left corner and continued through T= 200, 250, 300, 350 (46D-H). The consumers again began to grow (T= 350, 46H) and spread around the ring again. This was followed by another wave of production and consumption (T= 500-750, 46J-O).

In runs with lower diffusion (0.01) between consumers, the pulse wave traveled slow enough that the wave only moved part way around the entire ring before the internal pulse frequency allowed the remainder of the consumers to pulse, thus stopping the wave. With an even lower diffusion coefficient of 0.001, the wave moved 3 cells before stopping. With a diffusion coefficient of 0.01, the wave moved 10 cells before being stopped by the natural internal pulse frequency.

A different pattern developed when the producers and consumers in the model were distributed in a random pattern around the ring (the individual cell concentration of pro-

Figure 46. Simulation of pulse model (Figures 14 and 18) with cells in a linear ring and diffusion between consumers of each cell in ring (DK=.1). For each time unit (e.g. A=0) density of producer and consumer in the matrix is shown along with size class distribution. The time series from A to O summarizes the temporal pattern of totals in matrix. Initial conditions of consumers were set to near zero except for one "seed" consumer at lower left corner of matrix which was set to 100.

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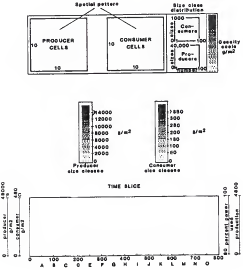
ducers and consumers was constant and the same as the homogeneous initial conditions) and diffusion set to zero (Figure 47). The output was based entirely on the random field from the initial conditions. Each individual cell model was producing and consuming at the same rate but there was no spatial synchronization of the cells. The pattern repeated itself over time (compare T=50, 47A with T=700, 47N).

When diffusion was set at a high level (0.1) between the consumers, with the same random initial distribution of producers and consumers, the resulting pattern was quite different (Figure 48). The pulsing consumers moved in a wave around the ring followed by a wave of production (T=50, 100, 150, 200, 250, 300; Figure 48A-F) followed by another wave of consumption beginning just prior to T=350 (48G). This was similar to the simulation in Figure 46 that began with a homogeneous initial distribution of producers and consumers and had waves of consumption and production around the ring.

When the model was run with random distribution of producers and consumers (Figure 49) and a low value of diffusion (DK=0.001), the spatial pattern that developed had some properties of both of the two previous runs. Because speed of movement was less with a lower value of diffusion, a number of focal points for pulse waves were generated which then run into each other and stop. The production follows the pattern of consumption with multiple foci.

Figure 47. Simulation of pulse model (Figures 14 and 18) with cells in a linear ring but without diffusion. For each time unit (e.g. A=0) density of producer and consumer in the matrix is shown along with size class distribution. The time series from A to O summarizes the temporal pattern of totals in matrix.Initial conditions of producers and consumers were set to random distribution around ring.



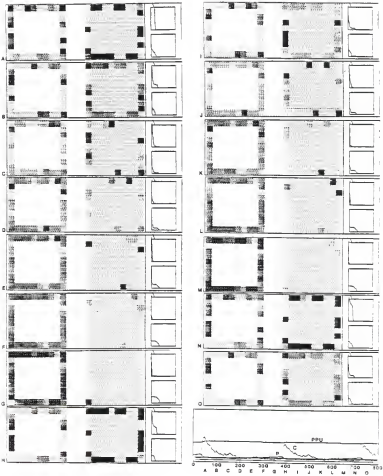

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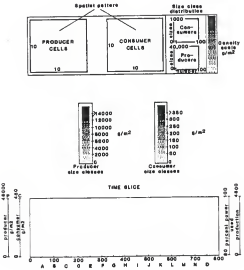
Figure 48. Simulation of pulse model (Figures 14 and 18) with cells in a linear ring and a high level of diffusion between consumers of each cell (DK=.1) and random distribution of producers and consumers around ring. For each time unit (e.g. A=0) density of producer and consumer in the matrix is shown along with size class distribution. The time series from A to O summarizes the temporal pattern of totals in matrix.



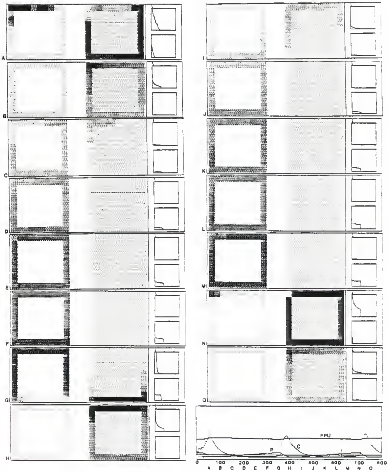

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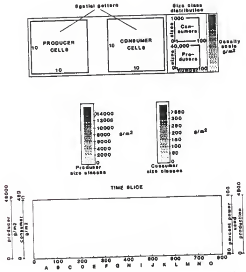
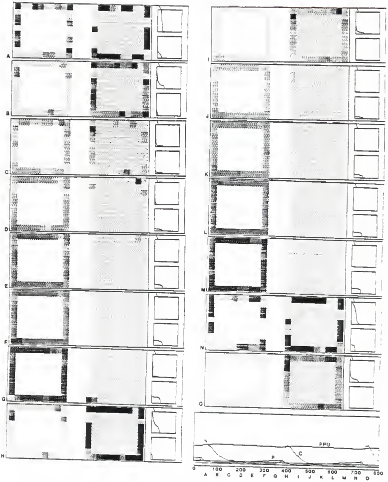
Figure 49. Simulation of pulse model (Figures 14 and 18) with cells in a linear ring and a low level of diffusion between consumers of each cell (DK=.001) and random distribution of producers and consumers around ring. For each time unit (e.g. A=0) density of producer and consumer in the matrix is shown along with size class distribution. The time series from A to O summarizes the temporal pattern of totals in matrix.





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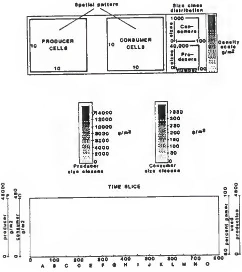
Simulation of Two Dimensional Surface Models

The simplest simulation of the two dimensional pulsing model, with no diffusion and an evenly distributed energy source (Figure 50), had a time series output identical to the basic pulse model (Figure 37a). Even though the model was disaggregated into 100 cells, each of the cells was identical. In this run, each of the cells was synchronized (by the initial conditions) and the pulsing was based only on the internal frequency of the model (T=250, 50E and T=600, 50L). There was little change in the size distribution of the producers and the consumers during the simulation.

The influence of an energy source that is hierarchically distributed from the center of the matrix outward generates a different pattern (Figure 51). The production was higher in the center of the matrix than at the outer edges. In this simulation without diffusion there was no edge effect. The first pulse came at the center of the matrix (highest input energy) and then moved outward to the edge in a series of pulses. The production and consumption then continued to oscillate. The frequency of pulsing in each individual cell depended on the intensity of the energy input to that cell (see also Figure 40a-f). The center cells pulsed at a higher frequency than the outer cells due to differences in input energy. The time series of the

Figure 50. Simulation of pulse model (Figure 14) with cells arranged in two dimensions (Figure 18) without diffusion and with a constant energy source. For each time unit (e.g. A=0) density of producer and consumer in the matrix is shown along with size class distribution. The time series from A to O summarizes the temporal pattern of totals in matrix.



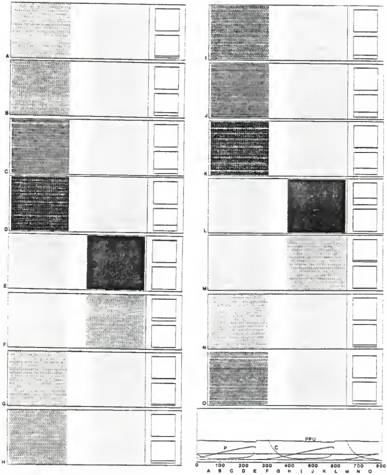

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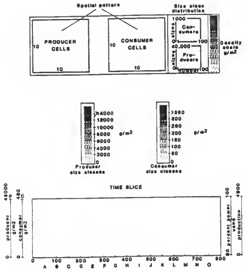
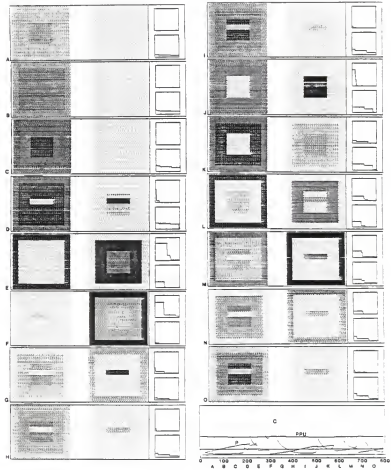
Figure 51. Simulation of pulse model (Figure 14) with cells arranged in two dimensions (Figure 18). Energy source hierarchically is distributed from center outward and no diffusion between cells. For each time unit (e.g. A=0) density of producer and consumer in the matrix is shown along with size class distribution. The time series from A to O summarizes the temporal pattern of totals in matrix.

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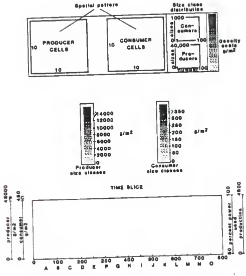
simulation had sharp peaks due to the different frequencies of pulsing of the independent cells. The size distributions of the producers and consumers were based on the input energy and are grouped accordingly. Without diffusion, the pattern formed was entirely dependent on the hierarchical pattern of the input energy.

The addition of diffusion between the consumers of each cell for the previous model smoothed out the time series for the consumers and producers (Figure 52). A low level of diffusion (DK=0.001) enabled the first pulsing cells (located at the center of the matrix) to affect the neighboring cells, thus spreading the pulse wave out over the matrix. In this simulation the size distribution of the producers and consumers tended to smooth out over time. The edge effects were minimized in this simulation by allowing the outer non-reactive ring of consumer cells to float at a value that was the average of the total consumers in the matrix.

Diffusion between the consumers at a low level had a much greater effect in this two dimensional version of the model than in the one dimensional ring version of the model. When the two dimensional version was run with a random energy source and a low diffusion coefficient (Figure 53, DK=0.001) the effect was similar to that seen in Figure 52. In this case, local foci of high productivity (caused by locally high values of input energy) led to pulses that spread over the entire matrix. This simulation was dif-

Figure 52. Simulation of pulse model (Figure 14) with cells arranged in two dimensions (Figure 18). Energy source is hierarchically distributed from center outward and diffusion is between consumers of each cell (DK=.001). For each time unit (e.g. A=0) density of producer and consumer in the matrix is shown along with size class distribution. The time series from A to O summarizes the temporal pattern of totals in matrix.



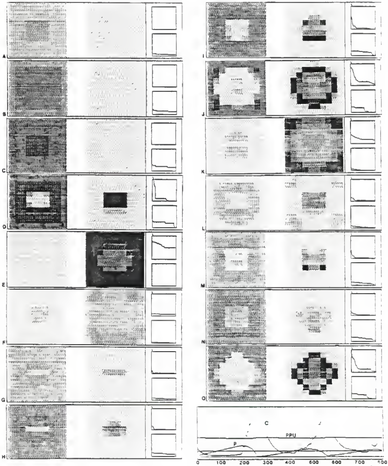

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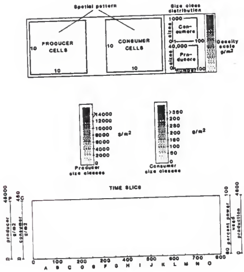
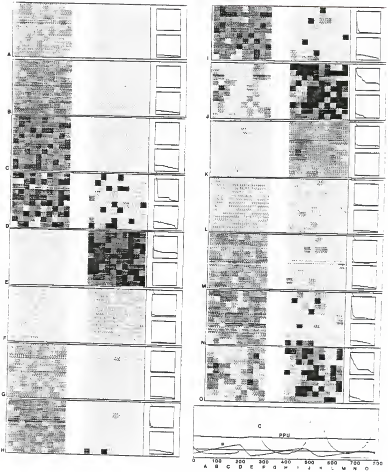
Figure 53. Simulation of pulse model (Figure 14) with cells arranged in two dimensions (Figure 18). Energy source is randomly distributed and diffusion is between consumers of each cell (DK=.001). For each time unit (e.g. A=0) density of producer and consumer in the matrix is shown along with size class distribution. The time series from A to O summarizes the temporal pattern of totals in matrix.

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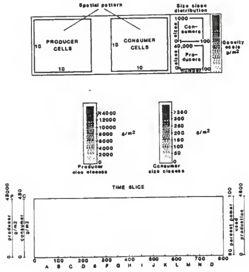
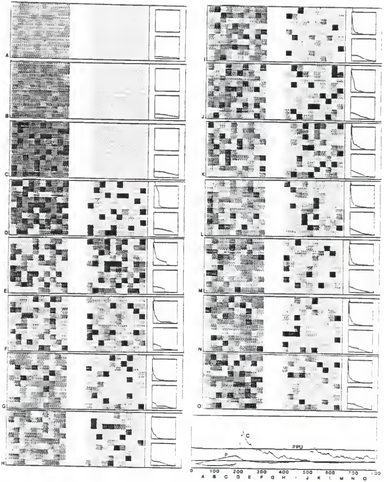
ferent from the random ring simulations (Figures 48 and 49) in that the input energy was randomly distributed while in the case of the ring model the initial producer-consumer pairs were randomly distributed. Little synchronization of the matrix occurred because the random energy distribution caused locally high concentrations of producers every time there was a pulse. In the simulation of the ring with randomly distributed producers and consumers, at a high level of diffusion the pulse wave moved fast enough to reset all of the producers and consumers to similar values. With a low diffusion value, the wave traveled so slowly that it did not get around the ring, and multiple foci of pulsing developed.

Simulation with diffusion between the nutrient compartments of each cell (Q4) of the model instead of to the consumers (Q3) can be seen in Figure 54. With a random distribution of energy and a high level of diffusion (DK=0.1) the pulsing was almost totally uncoupled. By the end of the run (T=750, Figure 54O) there was constant pulsing in one cell or another, and the overall level of producers as seen in the time series graph was fairly constant.

The spatial configuration of the model was also tested with a moving consumer. This is similar to the diffusion runs of the model but represents an active process with discontinuous (non-uniform) movement of consumers from cell to cell. The consumer was allowed to search for the largest producer to consume before moving. The model was tested

Figure 54. Simulation of pulse model (Figure 14) with cells arranged in two dimensions (Figure 18). Energy source is randomly distributed and diffusion between nutrient storages (Q4) of each cell is set to high level (DK=.1). For each time unit (e.g. A=0) density of producer and consumer in the matrix is shown along with size class distribution. The time series from A to O summarizes the temporal pattern of totals in matrix.

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with a hierarchical energy input and a consumer search length of 1 cell (Figure 55) and a search length set to 5 cells (Figure 56). The simulations are quite different in both the spatial patterns generated and in the time series graph of the simulation.

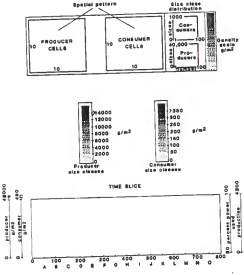
When limited to a search length of 1 cell, the consumption pattern moved like a wave from left to right across the producers after starting in the center. With a longer search length (Figure 56), the consumption began in the center and spread out in a circular pattern over the producers. There are two of these waves of consumption during the time of the simulation for the search length of 5. The run with a search length of 1 cell has slower consumption and only moves across the field once.

Rain Forest Gaps and Hierarchies

Size Class Distributions

Three different size class distributions (Figure 57) were generated from the data set from the radiation site at El Verde to characterize the hierarchical patterns in the vegetation. Figure 57a represents the distribution of plants by diameter. This can be compared to the data from Crow (1980) in Figure 8. The distribution of plants by crown diameter (Figure 57b) and by height (Figure 57c) was hierarchical. The sampling technique affected the results in the lowest size classes.

Figure 55. Simulation of the pulse model (Figure 14) with cells arranged in two dimensions (Figure 18). Moving consumer model with search length set to one cell, no diffusion and hierarchical energy distribution. For each time unit (e.g. A=0) density of producer and consumer in the matrix is shown along with size class distribution. The time series from A to O summarizes the temporal pattern of totals in matrix.



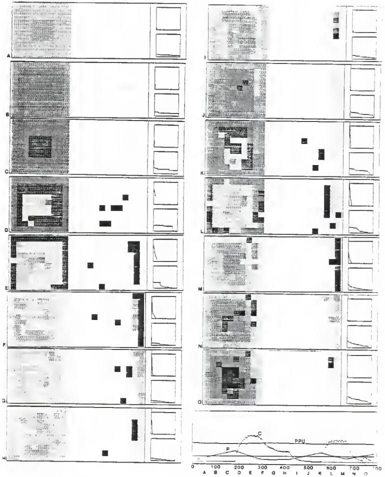

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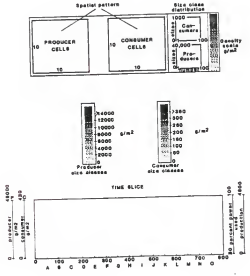
Figure 56. Simulation of the pulse model (Figure 14) with cells arranged in two dimensions (Figure 18). Moving consumer model with search length set to five cells, no diffusion and hierarchial energy distribution. For each time unit (e.g. A=0) density of producer and consumer in the matrix is shown along with size class distribution. The time series from A to O summarizes the temporal pattern of totals in matrix.



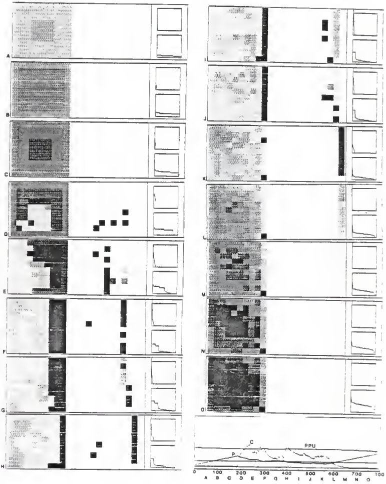

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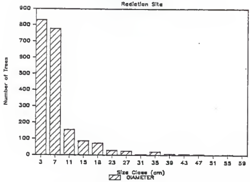
Figure 57. Size class distribution of trees at El Verde radiation site (November 1964)

(a) Size class distribution by diameter

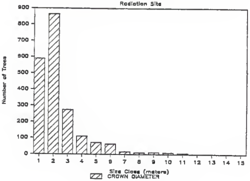
(b) Size class distribution by crown diameter

(c) Size class distribution by height

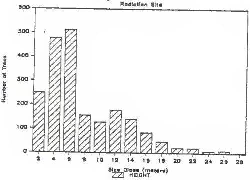
Diameter Distribution



Crown Diameter Distribution



Height Distribution



Gap Size Measurements

The distribution of cecropia gaps at El Verde fall into a hierarchical distribution (Figure 58). Figure 58a is the size distribution of all four of the photographic plots combined and Figure 58b shows the distributions of the individual plots. The percentage of the total area that is in the gap stage is 3.79% (Table 2). The values plotted in Figure 58 are the actual areas measured in square inches on the photograph. The figure shows a minimum size for the gaps and a hierarchical distribution.

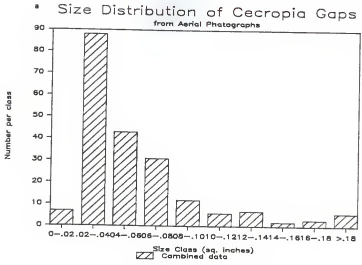
Comparison to Models

For each time slice that the spatial simulation model printed a spatial pattern of producers and consumers, it also printed a graph of the size distribution of the producers and consumers (just to the right of the spatial patterns). The format of the distribution graph is not the same as the size class distributions in Figure 57 but the size distributions do represent the same class size phenomenon. Depending on the energy input conditions and diffusion coefficients some of the size distributions had similar relationships to the natural distribution (see Figures 51, 53 and 56) while others are quite different (see Figure 50). The pulsing in Figure 50 is totally synchronous while the pulsing in Figures 51 and 53 are more spatially asynchronous.

Figure 58. Size distribution of *Cecropia* gaps in tropical rainforest at El Verde.

(a) Distribution of gaps in all five photographs.

(b) Distribution of gaps in each individual photograph.


a
Size Distribution of Cecropia Gaps
from Aerial Photographs
Number per class
90
80
70
60
50
40
30
20
10
0
0-.02 .02-.04 04-.06 06-.08 08-.10 10-.12 12-.14 14-.16 16-.18 >.18
Size Class (sq. inches)
Combined data

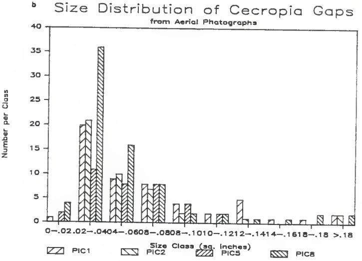

b
Size Distribution of Cecropia Gaps
from Aerial Photographs
Number per Class
40
35
30
25
20
15
10
5
0
0-.02 .02-.04 04-.06 06-.08 08-.10 10-.12 12-.14 14-.16 16-.18 >.18
Size Class (sq. inches)
PIC1
PIC2
PIC5
PIC8

Table 2. Area of gaps digitized from photographs of Luquillo tropical rain forest.

Picture number	1	2	5	8	Total
Number of gaps	53	43	35	74	205
Mean	0.0761	0.0517	0.0455	0.0473	0.0554
Std. Error	0.0212	0.0096	0.0043	0.0083	0.0066
Minimum	0.0093	0.0125	0.0094	0.0067	0.0067
Maximum	1.121	0.360	0.100	0.5525	1.121
Area % of total	5.38	2.97	2.12	4.66	3.785

* Means are not significantly different p=.005

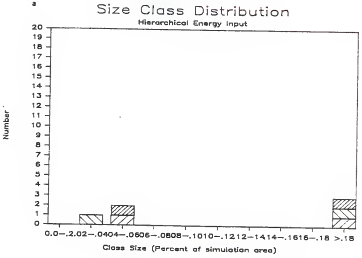
The gap size distribution was measured for a set of spatial simulations with input energy distributed hierarchically, evenly and randomly. Figure 59a represents a combined gap size distribution measured from a set of three different simulation runs using a hierarchical input energy source. The gap size distribution is skewed to one set of large gaps and a few smaller patches. With a random energy source the results (Figure 59b) resemble the size class distribution of the natural system (Figure 58) with more small patches and fewer large ones. With an evenly distributed input energy source and no diffusion, the system pulses in a synchronous manner that generates a gap the size of the simulation (100%) with each pulse. With diffusion present, the patch size is dependent on the edge effect. If the edge effect is canceled the result is the same; however with a diffusive loss or gain along the edge, the patch size is reduced from 100% due to the uncoupling of the synchronous pulsing at the edges.

Figure 59. Size distribution of gaps in tropical rainforest pulsing model simulation (Figures 14 and 18) at time =760.

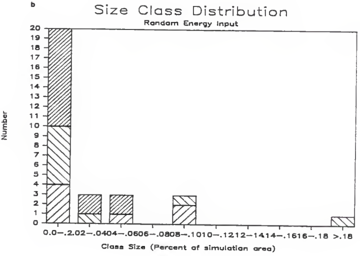
(a) Size class distribution from three separate model runs with hierarchical energy distribution.

(b) Size class distribution from three separate model run with random energy distribution.

a


Size Class Distribution
Hierarchical Energy Input
Number
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
0.0—.2.02—.0404—.0606—.0808—.1010—.1212—1414—.1616—.18 >.18
Class Size (Percent of simulation area)

b


Size Class Distribution
Random Energy Input
Number
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
0.0—.2.02—.0404—.0606—.0808—.1010—.1212—1414—.1616—.18 >.18
Class Size (Percent of simulation area)

CHAPTER 4

DISCUSSION

Many of the characteristics of ecosystem function were generated by the simulations in this dissertation. Energy increased with growth. Net production alternated with pulsing net consumption. Hierarchical patterns in space resulted from oscillations in time. Edge effects developed. There were similarities with succession observed in nature. Many characteristics of ecosystems were generated by minimodels that had autocatalysis, recycling, parallel pathways of different order, spatial intercell exchanges and hierarchical distribution of time constants. In other words, simple models emulated many features of more complex ecosystems.

The spatial model in this dissertation differed from many previous spatial ecosystem models that used individual species growing and interacting together (Botkin, Janak and Wallis 1972, Phipps 1979, Doyle 1982). This model was a unit ecosystem model that combined all of the species into compartmentalized production, consumption and nutrient storages. This simplified the model but kept many of the ecosystem characteristics.

Maximum Power Considerations

The class of models studied here duplicate real systems by reinforcing pathways that process more power. The feedbacks simulate useful power processing. These models link kinetics and energetics in ways observed in nature.

Power and Feedback With Paths of Higher Order

Systems that generate higher order pathways to capture varying energy flows may offer a competitive advantage. The maximum power implication is that as systems develop feedbacks (higher order pathways) they can extract more energy from the source. Lotka (1922) stated that as long as there was untapped available energy, systems were capable of growth when rates of flow increased through the system. Odum (1982 and 1983) added that as systems mature they feed back energy which amplifies other pathways and maximizes power. The multiple pathway configuration shown in the three path model provides a possible mechanism for this to occur. In the three path model simulations (Figures 19 - 27) the linear pathway had a fixed efficiency while the autocatalytic and quadratic pathways had variable efficiencies (see Figure 20 and 21) depending on the input power.

The development of multiple pathways in a system is incurred at some energy cost to the system. The energy costs associated with developing and maintaining the nonlinear pathways must be competitive to survive. For systems

with small storages (i.e. fast turnover times), the quadratic pathway can be non-functional (Figure 21, pathway J3). Because non-linear pathway flows are a function of both the energy source and the storage, there are conditions when the pathway has a threshold for operation (Figure 21, pathway J2 and J2+J3 and Figure 27 pathway J3). Low energy systems may not have enough energy available to allow development of these higher order pathways.

Human systems may be a good example of how these pathways may operate. Nomadic, subsistence societies can be considered as basically linear systems that utilize available resources with few or no feedbacks. By developing autocatalytic feedbacks, primitive societies move up to developing societies building structures to process more energy (farming, mining, transportation and manufacturing). As growth continues, systems develop within society that have higher order quadratic feedbacks to facilitate processing energy (communications, banking and finance, and information systems). Because the higher order pathways are dependent on storages and energy flows, the structures may not be stable with reduced energy.

For a system pathway to utilize fluctuating energy flows, it must have enough structure to sustain the system when the non-linear pathways are not functioning (at lower energy levels). While the nonlinear pathways were dependent on the frequency and amplitude of input energy (Figures 25, 26 and 27) the linear pathway had no frequency dependency

and thus provided energy to the system under all input regimes. A system with a combination of pathways then shows greater stability under fluctuating regimes and maximizes power with increasing energy inputs.

Multiple pathway models have been used to describe a variety of systems. A disaster model using multiple pathways (linear and autocatalytic) has been used to describe earthquakes and floods (Alexander 1978). Models of chemical reacting systems have often used multiple pathway models to describe the kinetics of the reactions ("Brusselator", Nicolis and Prigogine 1977 and "Oregonator", Field and Noyes 1974). "Chaotic systems" are often modeled with multiple non-linear pathways (Abraham and Shaw 1984b).

Effect of Hierarchies on Performance

Hierarchical subunits of a system generally have increasing turn-over times with increasing trophic levels (Allen and Starr 1982, Urban, O'Neill and Shugart 1987). The addition of an extra consumer (adding a level to the hierarchy) of the pulse model (Figure 15) must have the appropriate turnover time to survive. If the turn-over time was too short, not enough energy was available to that level of the hierarchy to sustain it and the added level did not survive (Figure 45a). If the turnover time was too long, the rate of power use dropped and the whole system collapsed (Figure 45c). The appropriate size consumer modified the output behavior of the model (pulsing with a longer period), but the system was stable and utilized slightly more power.

The highest level of the hierarchy in this model determined the frequency and scale of pulsing. Therefore there are optimum turnover times for maximum performance.

Conversely, as input power increases, a higher level of consumers may be supported. This was seen in the parallel production-consumption model (Figure 32d) and the pulse model (Figure 40c).

Power Used as a Function of Input Power

The general trend for all of the models tested here was that as the input power increased, the percent of input power that is utilized increased. This occurred in the three path model (Figures 21, 22, 23), the parallel production-consumption model (Figures 30e, 32e, and 36), the pulse model (Figure 40f) and the spatial models. This appears to be a function of the non-linear pathways that feed energy back to increase the efficiency with increasing available energy. Individual simulations of these models with only linear pathways did not show this behavior.

Threshold for Stable Feedbacks and Pulsing

The pulse model exhibited a double threshold phenomenon. At low power inputs the model did not pulse and at high power inputs the model did not pulse (Figures 37 and 40). In the middle power range, the model pulsed and the pulse frequency was a function of the input power. Localized maxima of power utilization may occur in the pulsing range due to synchronization of inputs with natural internal

frequencies (Richardson and Odum, 1981). This double threshold behavior has also been shown in a wide variety of prey-predator model configurations (Kuno 1987). Oscillating chemical reactions exhibit this multiple output state behavior (Field 1985).

At low power levels, the pulsing model supported a constant low amount of consumers (dependent on the linear pathway) while at high power levels the consumer was at a constant higher level (sustained by both the linear and quadratic pathways) with the producer at a low level. This was also the case in the chemical reactions and prey-predator models described above. Models with this behavior may describe a variety of ecosystems that show various levels of producers and consumers. A grassland ecosystem such as the Serengeti (McNaughton 1985) may be an example of low levels of producers supporting high levels of consumers.

A similar dependence of the highest trophic level on the input energy was also exhibited with the parallel production-consumption model (Figure 32) although this model did not pulse. It should be noted with this model that the consumer level increased and the 'climax' producer did not.

The pulsing model did not pulse when the consumer quadratic pathway (Figure 38) was removed, the consumer built up to a steady state, and the percent power used declined. There was a lot of structure in the higher level of the hierarchy but the system was not effective at using the extra power that was available. Competitively, a system

with this structure may be at a disadvantage and could be eliminated through consumption by a higher level of the hierarchy or competition by other systems at the same level of the hierarchy.

If a system was not materials conservative (feedbacks from the consumer to the nutrient storage cut off or diverted, Figure 39) then the system ceased pulsing and ran down. The system had no feedback pathways and so did not capture all of the available energy.

Implications for Succession

Role of Individual Units

Early successional producers can be thought of as preparing the way for succession to occur. Although early successional species may have other roles, in the parallel production-consumption model (Figure 13) they can be seen as providing an energy source to the consumer level of the model as the rest of the system builds up. When the early successional species was at a low level, the consumer level (Q4) remained low (Figure 35). This low consumer level did not feed back enough to the producers to stabilize the system and the system crashed. As the early successional species (Q3) reached a threshold initial condition, sufficient structure was built and the system progressed to a steady state.

If the consumer level in a successional system is too low then the system may not be stable. In the parallel production-consumption model, the consumer provided a feedback on the producers through the input production multiplier and through consumption on the producers. When the consumer was at a level that was too low, succession as depicted by the model (Figure 33 and 36) did not begin. At some initial threshold level of consumers, the model proceeded through a successional sequence.

In developing management plans for revegetating sites disturbed by mining, intensive agriculture or natural disturbances, it is imperative that careful attention be paid to the whole structure of the ecosystem that is being rebuilt. Without the proper mix of early, middle, and late successional producers along with a set of consumers that match the producers, the restablishment of a natural successional sequence may be retarded or destroyed.

Succession and Pulsing

The role of pulsing in succession may be that in some systems it is necessary to have the pulsed recycle to maintain energy flows near maximum levels. Several cases of the pulsing model (Figures 38 and 39) showed that when recycling was disturbed power use dropped. Certain types of sucession may need an alternation of production and consumption at a frequency that allows the maximum use of available energy. Systems in which available nutrients become bound in the

biomass may benefit by the fast release from a pulse of consumption and recycle.

Spatial Pattern Formation

Synchronous vs. Asynchronous Systems

When a spatially organized system is totally synchronized (all subunits behaving as one), the system may be like a monoculture with little pattern formation other than that of the local source inputs. In this state, pattern diversity is low. Where cells are not all synchronized with each other, patterns can develop that are dependent on the asynchronous nature of the individual subunits as well as the local energy sources.

When the spatial model was simulated with all of the individual cells uncoupled (not linked through intercell diffusion processes) and totally synchronized (all cells begun with the same initial conditions and an even energy distribution), no pattern was generated (Figure 50). The level of producers and consumers was the same in each cell at every point in time.

Any variation in the energy input over the matrix area lead to individual cells pulsing at frequencies depending on the energy level local to that area (Figure 51). Although the pattern was quite different from the synchronized one, the energy use is the same (Table 5 in Appendix).

Coupling of Spatial Units by Diffusion Processes

In any ecosystem, spatially distributed subunits are connected to each other through a variety of processes. Nutrients and seeds can be carried spatially by transport from wind, water and animal activity. Predation by consumers tends to reorganize the vegetation community structure. The degree to which subunits are connected to one another is strongly reflected in the patterns that may develop.

Connectivity between subunits tends to decrease the asynchronous behavior caused by local energy differences. With a low level of diffusion (Dk=.001) the pulsing behavior was propagated across cell boundaries (compare Figure 52 with Figure 51). At higher levels of diffusion (not shown), the effect was to increase the synchronous nature of the pulsing across the matrix. Energy use with various levels of diffusion did not change appreciably (Table 5 in Appendix).

In a single dimension system (ring model) the effect of diffusion was similar. At high levels of diffusion (Figure 48) pulses were propagated around the entire ring, while at a lower level of diffusion the propagation was confined to local areas (Figure 49). The asynchronous pulsing (Figure 47) was thus organized into a more synchronized spatial pattern depending on the degree of connection between the individual cells.

The level of the hierarchy in which inter-cell coupling takes place plays an important part in the development of spatial patterns. When this coupling took place at the level of nutrient exchange from cell to cell (Figure 54), the effect was hardly detectable, even at high diffusion levels.

Spatial patterns generated are not totally dependent on the natural energy inputs but organize using those natural energy regimes. Spatial diversity thus depends on the the landscape energy pattern, the interactions between the subunits, the hierarchy level of the interaction and the existing pattern of vegetation.

Most of the models in this dissertation used only diffusive coupling between spatial subunits of the model. Many systems have more complex interactions between subunits than this simple linear coupling. The active transport systems of biological systems are good examples of the more complex coupling that can occur in living systems. The moving consumer model represents a more complex coupling between individual cell units.

Organization by Higher Level Consumers

The role of the consumer in these models was very important in organizing pattern formation. When the spatial model was simulated with one consumer spread evenly over the matrix, the result was exactly the same as when the model was simulated with all cells uncoupled and a single consumer in each cell of the matrix (Figure 50). In this case, the

synchronous organization of individual consumers (100 total) over the entire matrix of cells mimiced the effects of a large consumer with the same territory. The percent power used for each of these simulations was the same (Table 5 and 6 in Appendix).

Coupling of the consumers from cell to cell by diffusion organized the consumer action over the whole matrix depending on the strength of that coupling. Low levels of diffusive coupling generated local areas of organization by the consumers (Figure 53) while strong coupling organized the disturbance over the entire matrix, (not shown but similar to Figure 50).

Active coupling between subunits by consumers was simulated using a moving consumer model (Figures 55 and 56). In this case, very different patterns were formed with a smaller number of consumers. The action of organizing the entire landscape (10x10 matrix) was achieved with fewer consumers. The energy use was not significantly different from the other spatial simulations (Table 7 in Appendix). The efficiency of active coupling may be higher than passive (diffusion) coupling.

Organization at a higher level tends to have a larger effect in generating patterns. Some of this may due to a type of 'memory' generated in the landscape by the disturbance-succession sequence generated by these pulsing production consumption models. As the system pulses, small differences between individual cells generate further dis-

continuities. These small differences act as information storage for future pattern development.

Power Use and Edge Effects

No system exists in an infinite plane without edges. Edges were manipulated in the spatial models to understand their role in pattern formation. Some of the simulations allowed consumers to diffuse into or out of the spatial matrix at high and low levels of diffusion.

When the consumer level on the outside ring was kept at a low value (0.0), the percent power used decreased (Table 8 in Appendix) with increasing rates of diffusion. If the outside buffer had a high value for the consumer (Q3 equal 100) then just the reverse was seen. With increasing rates of diffusion there was an increase in the percent power used. This implies that consumer exchange can act as an energy source or a drain in a system depending on the relationship of the system to its surrounding area through its edges.

General Principles

The following are some general principles suggested by model studies, which may be useful hypotheses in future experimental studies.

1) Multiple pathways increase efficiencies and enable better use of fluctuating energy sources. Multiple steady states can result from one basic configuration. The

kinetics of these pathway configurations are similar to others studied by chaos theory, bifurcation theory and catatastrophe theory.

2) Hierarchical structure is expressed in kinetics as increasing turnover times with increasing territory. Pathways of control of production-consumption systems must match the turnover time of the appropriate hierarchical level in order to cause reinforcement.

3) In early successional systems there may be critical minimum stocks of producers and consumers for a system to grow.

4) Similar maximum power processing may be achieved by a wide variety of spatial patterns.

5) Connectivity in systems has a greater role in pattern formation at higher levels of the hierarchy. Control of patterns and patchiness through consumer control is highly dependent on the spatial connectivity of the consumers.

6) Patch size may be related to the turnover time of the consumer and the spatial connectivity of the consumers.

7) Some of the great complexity of ecosystems may be simplified for human comprehension if varied mechanisms can be grouped according to the basic kinetics, energetics and hierarchical roles they perform.

APPENDIX

Table 3.

Coefficient values for parallel production-consumption model in Figure 13.

K1	.ØØ3	Production coefficient for Q1
K2	.ØØ5	Production coefficient for Q2
K3	.ØØ7	Production coefficient for Q3
D1	.1	Drain coefficient for Q1
D2	.2	Drain coefficient for Q2
D3	.3	Drain coefficient for Q3
K7	.ØØ6	Consumption coefficient for Q1
K8	.Ø15	Consumption coefficient for Q2
K9	.Ø4Ø	Consumption coefficient for Q3
D4	.Ø8	Drain coefficient for Q4
KØ	.1	Intake coefficient for Q4
F1	.Ø1	Feedback loss coefficient for Q4

Table 4

Steady state values, coefficients and flows for pulse model.

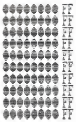
J0	100.	Sunlight normalized to 100
Jk	4.0817993	Available sunlight at ground level
Q1	1000.	Labile storage (Primary producer)
Q2	10000.	Stored Biomass
Q3	50.	Pulse consumer
Q4	30000.	Nutrients (Available carbon)

K1	.00000417	R1	510.63309
K2	.5	R2	500.
K3	.05	R3	50.
K4	.45	R4	450.
K5	.00005	R5	.5
K6	.00045	R6	4.5
K7	.0000002	R7	5.
K8	.0000018	R8	45.
K9	.000002	R9	50.
K10	.00000417	R10	510.63309
K11	.0005	R11	5.
K12	.05	R12	2.5
K13	7.833E-7		

(Jordan and Drewry 1969, Odum and Pigeon 1970, and Brown, Lugo, Silander and Liegel 1983)

Figure 60. Character set for displaying spatial graphs on GIGI computer terminal suitable for use with screen copy onto printer. Each dot pattern is represented by the hexadecimal code on the left edge of each plot.

(a) 80 dots
(b) 40 dots
(c) 27 dots
(d) 20 dots
(e) 16 dots
(f) 12 dots
(g) 7 dots
(h) 3 dots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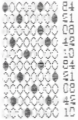
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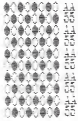
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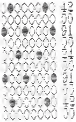
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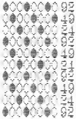
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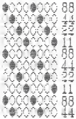
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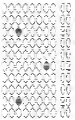
h

Table 5. Percent power used as a function of input energy sources and diffusion in different ecosystem levels.

	Successional	Steady state
	(a) No Diffusion	
Energy Distribution	Percent Power Used	
Hierarchical	96.5	96.6
Even	96.5	96.6
Random	96.6	96.6

(b) Diffusion between nutrient (Q4) tanks (Successional initial conditions)

Diffusion rate	.001	.01	.1
Energy Distribution			
	Percent Power Used		
Hierarchical	96.5	96.5	95.5
Even	96.5	96.5	96.5
Random	96.6	96.6	95.6

(c) Diffusion between consumer (Q3) tanks (Successional initial conditions)

Diffusion rate	.001	.01	.1
Energy Distribution			
	Percent Power Used		
Hierarchical	96.6	96.6	96.6
Even	96.5	96.5	96.5
Random	96.6	96.5	96.5

(a) Model DSP1. See Figure 50 for example run.

(b) Model DSP1. See Figure 54 for example run.

(c) Model DSP1QZ. See Figure 53 for example run.

Table 6. Percent power used for various runs of DSP1C spatial model having only one consumer equally distributed across the entire production matrix.

	Successional state	Steady state
High initial condition for consumer Q3 (5000).		
Hierarchical	96.5	96.5
Even	96.5	96.6
Random	96.4	96.4
Low initial condition for consumer Q3 (50).		
Hierarchical	96.5	96.4
Even	96.5	96.4
Random	96.4	96.3

Table 7. Percent power used for DSP100 model as a function of search length and input energy type.

Search length (cells)	Successional state			Steady state	
Hierarchical distribution					
1	96.4	(17)	(a)	96.5	(31)
2	96.6	(28)		96.6	(39)
3	96.6	(36)		96.6	(39)
4	96.6	(36)		96.6	(43)
5	96.5	(33)	(b)	96.5	(45)
Even distribution					
1	95.7	(15)		crash	(13)
2	96.4	(30)		96.5	(30)
3	96.4	(38)		96.5	(34)
4	96.4	(38)		96.5	(42)
5	96.5	(32)		96.5	(40)
Random distribution					
1	96.4	(20)		95.7	(32)
2	96.6	(34)		96.6	(38)
3	96.6	(40)		96.5	(44)
4	96.6	(42)		96.5	(45)
5	96.6	(41)		96.6	(45)

(n) indicates number of consumers at end of simulation.
(a) see Figure 55
(b) see Figure 56

Table 8. Percent power used as a function of different energy input sources and diffusion rates. Edge effect model with different levels of consumers (Q3) on outside (buffer) edge of spatial matrix.

Diffusion rate		.001	.01	.1
Value of Q3 on outside edge	Energy Distribution	Percent Power Used		
0.0	Hierarchical	96.6	96.5	96.1
	Even	96.5	96.5	95.9
	Random	96.6	96.5	95.9
50.	Hierarchical	96.6	96.5	96.7
	Even	96.6	96.7	96.6
	Random	96.6	96.7	96.6
100.	Hierarchical	96.6	96.7	96.8
	Even	96.6	96.8	96.8
	Random	96.6	96.8	96.8

```
      PROGRAM SUC10
C     SUCGGX
C     VERS 1.1
C     FEBRUARY 5, 1984
C
      BYTE FILE(16),ESC,DES(40)
      REAL M1,M2,M3,M4,M9
      REAL K1,K2,K3,K4,K5,K6,K7,K8,K9,K0,L1,L2,L3,J,J0
      DIMENSION FILNAM(6),IY(50,200)
      DATA FILE/16*0/
      DATA DES/40*0/
      FT1(A,B)=ABS(AINT(A/B)-A/B)
      D(X,Y)=(X/Y)*ALOG(X/Y)
C
C
      WRITE(5,100)
100   FORMAT(1X,'  SUCGGM GENERATES 6 DATAFILES',
     &/'  BE SURE THAT THEY DONT ALREADY EXIST',
     &/'  WHAT IS THE DATA FILE FOR THIS MODEL RUN ?')
      READ(5,101)(FILE(I),I=1,16)
101   FORMAT(16A1)
C
C
C     WRITE(5,1011)
C1011 FORMAT(' WHICH Q TO SAVE (1,2,3,4,5=% POW USED,6=BIOMSS)'$)
C     READ(5,1012)IQSAV
C1012 FORMAT(I3)
      WRITE(5,1013)
1013  FORMAT('  WHAT IS THE INCREMENT IN J0? [R]  '$)
      READ(5,1014)XINC
1014  FORMAT(G15.5)
C
C
c     WRITE(5,99)
c 99  FORMAT('   HOW LONG TO RUN? ')
c     READ(5,98)TIME
c 98  FORMAT(F6.0)
      TIME=100.                               !X.1
C     WRITE(5,981)
C981  FORMAT('  DO YOU WANT A HARDCOPY? (1-YES,0-NO)'$)
C     READ (5,982)ICOPY
C982  FORMAT(I2)
      OPEN(UNIT=1,NAME=FILE,TYPE='OLD',FORM='UNFORMATTED')
      READ(1)E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,E11,E12,E13,E14,E15,
C     COEFFICIENTS ************************************************
     +NUM,K0,K1,K2,K3,K4,K5,K6,K7,K8,K9,D1,D2,D3,D4,L1,L2,L3,F1
     +,J0,Q1INIT,Q2INIT,Q3INIT,Q4INIT
      CLOSE(UNIT=1)
C     INITIAL CONDITIONS*********************************************
      XJ0INI=J0
      NSLICE=25
      NCNTS=150
1     CONTINUE
C
```

```
C       BIG OUTER LOOP
C
        DO 1062 IQSAV=1,6
C
C
        NRUN=0
2       CONTINUE
        J0=XJ0INI+NRUN*XINC
        NRUN=NRUN+1
        T=0
        PERCNT=0
        PAVAIL=0
        PUSED=0
        DUSED=0
        Q9=0
        BIOMSS=0
        M1=0
        M2=0
        M3=0
        M4=0
        M9=0
        P=0
        BMAX=0
        Q1=Q1INIT
        Q2=Q2INIT
        Q3=Q3INIT
        Q4=Q4INIT
        Q1SIZE=30.
        Q2SIZE=5.
        Q3SIZE=1.
        Q4SIZE=20.
C       SET OUTPUT VECTOR AND FLAG **********************************
        DT=.1
C       WRITE(5,108)DT
C 108   FORMAT('  TIME INTERVAL DT= ',F5.3)
C       ISTEP=1/DT                          !DT'S PER T
C       IPLOT=0                             !PLOTTING INTERVAL IN DT'S
C       ITCNT=0                             !ITERATION COUNTER
C       WRITE(5,1081)
C1081   FORMAT(' WHAT IS PLOTTING INTERVAL PER TIME UNIT [I] '$)
C       READ(5,1082)IPLOT
C1082   FORMAT(I2)
C       WRITE(5,1083)
C1083   FORMAT(1X,' INPUT VALUES FOR SIZES Q1-Q4 [R] '$)
C       READ (5,1084)Q1SIZE,Q2SIZE,Q3SIZE,Q4SIZE
C1084   FORMAT(4F8.3)
C       WRITE GIGI STARTUP INFORMATION
C       CALL GGON
C       CALL GGINIT
C       CALL GGERA
C       CALL GGAXIS(0,0,767,479)
C       CALL GGBOX(7,0,0,767,479)
C       CALL GGBOX(7,0,0,767,350)
C
```

```
C       XDT=DT/10.
C       START OF LOOP ************************************************
 5      T=T+DT
C       ITCNT=ITCNT+1
C       RATE EQUATIONS***********************************************
        J=J0/(1+L1*Q1*Q4+L2*Q2*Q4+L3*Q3*Q4)
        EUSED=J0-J
        R1=DT*K1*Q1*Q4*J
        R2=DT*K2*Q2*Q4*J
        R3=DT*K3*Q3*Q4*J
        R4=DT*Q1*D1
        R5=DT*Q2*D2
        R6=DT*Q3*D3
        R7=DT*K7*Q1*Q4
        R8=DT*K8*Q2*Q4
        R9=DT*K9*Q3*Q4
        R0=DT*D4*Q4
C       LEVEL EQUATIONS *********************************************
        Q1=Q1+R1-R4-R7
        Q2=Q2+R2-R5-R8
        Q3=Q3+R3-R6-R9
        Q4=Q4+K0*(R7+R8+R9)-R0-F1*(R1+R2+R3)
        Q9=R1+R2+R3+K0*(R7+R8+R9)
        DRAIN=(R4+R5+R6+R0)+(1.-K0)*(R7+R8+R9)
        BIOMSS=Q1+Q2+Q3+Q4
C       M1=AMAX1(M1,Q1)
C       M2=AMAX1(M2,Q2)
C       M3=AMAX1(M3,Q3)
C       M4=AMAX1(M4,Q4)
C       M9=AMAX1(M9,Q9)
C
C
C       P1=Q1/Q1SIZE
C       P2=Q2/Q2SIZE
C       P3=Q3/Q3SIZE
C       P4=Q4/Q4SIZE
C       P1=AMAX1(P1,1E-5)
C       P2=AMAX1(P2,1E-5)
C       P3=AMAX1(P3,1E-5)
C       PMAX=P1+P2+P3+P4
C       DIVERS=-(D(P1,PMAX)+D(P2,PMAX)+D(P3,PMAX)+D(P4,PMAX))
C
D       WRITE(5,103)P1,P2,P3,P4,PMAX
D103    FORMAT(1X,5(2X,G12.5))
C
C
C       BMAX=AMAX1(BMAX,BIOMSS)
        P=P+Q9
        PAVAIL=PAVAIL+J0*DT
        PUSED=PUSED+EUSED*DT
        DUSED=DUSED+DRAIN
        PERCNT=EUSED/J0
C
C       FIND WHICH Q TO SAVE
```

```
20000   GOTO(21000,22000,23000,24000,25000,26000)IQSAV
        GOTO1101
21000   IY(NRUN,INT(T*1.5+1))=INT(Q1/.5)
        GOTO1101
22000   IY(NRUN,INT(T*1.5+1))=INT(Q2/.5)
        GOTO1101
23000   IY(NRUN,INT(T*1.5+1))=INT(Q3/.5)
        GOTO1101
24000   IY(NRUN,INT(T*1.5+1))=INT(Q4/.5)
        GOTO1101
25000   IY(NRUN,INT(T*1.5+1))=INT(PERCNT*1000.)
        GOTO1101
26000   IY(NRUN,INT(T*1.5+1))=INT(BIOMSS/.5)
        GOTO1101
C
C       SKIP PLOTTING IN THIS VERSION
C
C
C       GOTO 1101
C       IF(FT1(T,.1).GE.DT)GOTO 1101
C       IF(ITCNT.LT.IPLOT)GOTO1101
C       ITCNT=0
C       IX=T*7.
C       IY=Q1
C       CALL GGPLT(6,IX,IY,1)   !YELLOW FOR CLIMAX SPECIES
C       IY=Q2
C       CALL GGPLT(1,IX,IY,1)   !BLUE FOR TRANSITIONAL SPECIES
C       IY=Q3
C       CALL GGPLT(2,IX,IY,1)   !RED FOR WEEDS
C       IY=Q4
C       CALL GGPLT(3,IX,IY,1)   !MAGENTA FOR CONSUMERS
C       IY=Q9/DT
C       CALL GGPLT(4,IX,IY,1)   !GREEN FOR PRODUCTIVITY
C       IY=BIOMSS
C       CALL GGPLT(5,IX,IY,1)   !CYAN FOR BIOMASS
C
C
C       IY=EUSED*100/J0             !SCALE EUSED TO 0-100
C       CALL GGPLT(7,IX,IY+350,1) !PLOT POWER USED  WHITE
C       IY=(DRAIN/DT)*100/J0       !SCALE DRAIN TO 0-100
C       CALL GGPLT(5,IX,IY+350,1) !CYAN FOR DRAINS
C       IY=DIVERS*50
C       CALL GGPLT(2,IX,IY+350,1)
1101    IF(T.LT.TIME)GOTO 5
        WRITE(5,11011)J0,Q1,Q2,Q3,Q4,PERCNT*100.,BIOMSS
11011   FORMAT(1X,7(1X,F10.4))
        IF(NRUN.LT.NSLICE)GOTO2
        CALL ASSIGN(2,'SUCMANY',6)
        ENCODE(40,25001,DES)IQSAV,FILE
25001   FORMAT(1X,' TANK Q',I1,' FOR DATA FILE ',16A1)
        WRITE(2)(DES(I),I=1,40),NSLICE,NCNTS,
     + ((IY(JCNT,KCNT),KCNT=1,NCNTS),JCNT=1,NSLICE)
        CLOSE(UNIT=2)
        WRITE(5,1061)IQSAV
```

```
1061    FORMAT('  END OF RUN # ',I4)
1062    CONTINUE

C       ESC=27
C       IF (ICOPY.EQ.0)GOTO1102
C       WRITE(3,11021)
C11021  FORMAT(' S(H)')
C       CALL GGERA
C1102   CALL GGOFF
C       WRITE(5,1009)ESC,ESC,ESC
C1009   FORMAT(1X,A1,'Prtm1',A1,'®',A1,'[H'//
C      & '  INITIAL VALUES OF VARIABLES')
C       WRITE(5,114)
C       WRITE(5,112)Q1INIT,Q2INIT,Q3INIT,Q4INIT,0.,0.
C       WRITE(5,111)
C 111   FORMAT('   MAXIMUM VALUES OF VARIABLES  ')
C       WRITE(5,114)
C 114   FORMAT(6X,'Q1',7X,'Q2',7X,'Q3',7X,'Q4',6X,'PROD',5X,'BIOMASS')
C       WRITE(5,112)M1,M2,M3,M4,M9/DT,BMAX
C 112   FORMAT(' ',6F9.3)
C       WRITE(5,113)
C 113   FORMAT('   FINAL VALUES OF VARIABLES')
C       WRITE(5,114)
C       WRITE(5,112)Q1,Q2,Q3,Q4,Q9/DT,BIOMSS
C       WRITE(5,115)PAVAIL,P,PUSED,(PUSED/PAVAIL)*100,DUSED
C 115   FORMAT(
C      &1X,' ENERGY AVAILABLE =    ',F12.4/
C      &1X,' TOTAL PRODUCTIVITY = ',F12.4/
C      &1X,' ENERGY USED =        ',F12.4,' PERCENT USED =  ',F12.4/
C      &1X,' ENERGY DRAINED =     ',F12.4)
C       WRITE(5,116)
C 116   FORMAT(6X,'K0',8X,'K1',8X,'K2',8X,'K3',8X,'K7',8X,'K8',8X,
C      +'K9',8X,'F1')
C       WRITE(5,117)K0,K1,K2,K3,K7,K8,K9,F1
C 117   FORMAT(' ',8(2X,F8.4))
C       WRITE(5,118)
C 118   FORMAT(6X,'D1',8X,'D2',8X,'D3',8X,'D4',8X,'L1',8X,'L2',8X,
C      +'L3',8X,'J0')
C       WRITE(5,117)D1,D2,D3,D4,L1,L2,L3,J0
C       WRITE(5,119)DT,TIME
C 119   FORMAT('  DT THIS RUN = ',F6.4,' TOTAL T= ',F6.2)
C       WRITE(5,120)(FILE(I),I=1,16)
C 120   FORMAT('  DATA FILE DESIGNATION FOR THIS RUN ',16A1)
C       WRITE(5,121)Q1SIZE,Q2SIZE,Q3SIZE,Q4SIZE
C121    FORMAT(3X,'Q1SIZE Q2SIZE Q3SIZE Q4SIZE'/1X,4F7.1)
C       IF(ICOPY.EQ.0)GOTO1201
C       CALL GGON
C       WRITE(3,11021)
C       CALL GGOFF
1201    END
```

```
1 REM THREPATH MODEL VERSION 7/1/84
2 REM  WITHINPUT COEFFICIENTS CHANGED
3 REM NAME=> TPMOD7.BAS
90 PRINT "WHAT IS VALUE FOR ENERGY INPUT (J0-J1)"
91 INPUT J1
100 REM AND PRINT FNV$(C,X,Y) FOR PLOTTING VECTORS. C=COLOR(1-7)
110 PRINT "DO YOU WANT GRAPHICS ON" ® INPUT Q$
120 IF Q$<>"Y" GO TO 150
130 PRINT CHR$(27)+"PpS(E)W(R,I(G),P1,N0,A0,S0)S(A[0,479][767,0])"
140 DEF FNV$(C,X,Y)="W(I"+STR$(C)+")V["+STR$(X)+","+STR$(Y)+"]"
150 DEF FNP$(C,X,Y)="W(I"+STR$(C)+")P["+STR$(X)+","+STR$(Y)+"]V[]"
160 DEF FNT$(C,N,A$)="W(I"+STR$(C)+")T(S"+STR$(N)+")'"+A$+"'"
170 DEF FNB$(C,X,Y,X1,Y1)=FNP$(C,X,Y)+FNV$(C,X,Y1)+FNV$(C,X1,Y1)
    +FNV$(C,X1,Y)+FNV$(C,X,Y)
180 A$=CLK$
190 A9=TTYSET(255,132)
200 N9=-1.8
210 T9=1
220 W=0
230 Q=100
240 K1=.5
250 K2=1.00000E-03
260 K3=1.00000E-06
270 K4=.2
275 K6=K1
276 K7=10*K2
277 K8=10*K3
280 T=0
290 A$="Threepath Model"
300 PRINT FNP$(7,626,475);FNT$(7,1,A$)
310 PRINT FNB$(7,620,456,767,479)
330 PRINT FNB$(7,0,0,767,479)
340 PRINT FNP$(7,0,270);FNV$(7,767,270)
350 PRINT FNP$(7,0,380);FNV$(7,767,380)
360 PRINT FNP$(7,0,244);FNV$(7,767,244)
370 J0=J1/2+COS(W*T/57.2958)*J1/2
380 J9=J0/(1+K6+K7*Q+K8*Q*Q)
390 P1=P1+J0-J9
400 J7=J7+J0
410 R1=K1*J9
420 R2=K2*Q*J9
430 R3=K3*Q*Q*J9
440 R4=K4*Q
450 Q9=T9*(R1+R2+R3-R4)
460 Q=Q+Q9
470 X0=R1+R2+R3
480 X1=100*R1/X0
490 X2=100*R2/X0
500 X3=100*R3/X0
510 IF Q$="Y" THEN 580
520 PRINT "J0=";J0,"J9=";J9,"T=";T
530 PRINT "Q=";Q,"Q9=";Q9
540 PRINT "R1=";R1,"R2=";R2,"R3=";R3,"R4=";R4
550 PRINT "X1=";X1,"X2=";X2,"X3=";X3
```

```
560 PRINT
570 IF Q$<>"Y" THEN 640
580 PRINT FNP$(1,T*2,X1+275),FNP$(2,T*2,X2+275)
   ,FNP$(3,T*2,X3+275),FNP$(4,T*2,5+J9/1)
590 PRINT FNP$(5,T*2,J0/100+5)
600 PRINT FNP$(7,T*2,Q/1000+385)
610 PRINT FNP$(4,600,270);"T(S1)'JR=";J9;"'"
620 PRINT FNP$(6,T*2,170+(100*J9/J0))
630 Q7=Q7+Q ® REM TOTAL Q TO GET AVERAGE
640 T=T+T9 ® IF T<360 THEN 370
650 PRINT FNP$(4,600,270);"T(S1)'   ";"                '"
660 J5=P1/J7*100
670 PRINT FNP$(7,0,270);"T(S1)'POW USED=";P1
   ;"POW AVAIL=";J7;"PERCENT USED=";J5;"AVE Q=";Q7/T;"'"
680 INPUT X
690 PRINT CHR$(27)+"®"
700 PRINT P1/J7;"FRACTION OF TOTAL POWER USED"
710 END
```

```
C
C
C       GIGI GRAPHICS SUBROUTINE PACKAGE
C       WRITTEN BY JOHN R. RICHARDSON
C
C       SEPTEMBER 1982
C
C       VERS 11:  ALL UPDATES AND CURRENT TO SEPTEMBER 1982
C
C       VERS 12: FEBRUARY 28 1984 ADDITIONS
C               ADDED GGPLOT (CALL TO GGPLT)
C               ADDED GGDMP  (HARDCOPY DUMP)
C               ADDED GGVERS
C
C       ALL I/O IS TO LOGICAL UNIT 3
C
C*********************************************************************
C       THE NORMAL CALLING SEQUENCE TO SET UP THE GIGI WOULD BE      C
C       AS FOLLOWS:                                                  C
C                                                                    C
C       CALL GGON                     !TURNS GRAPHICS ON             C
C       CALL GGINIT                   !SENDS NORMAL INITIALIZATION   C
C       CALL GGERA                    !ERASE THE SCREEN              C
C       CALL GGAXIS(0,0,767,479)      !SETS NORMAL AXIS WITH ORIGIN  C
C                                     ! AT THE LOWER LEFT CORNER     C
C*********************************************************************
C       TASKBUILDING USING THE GIGI ROUTINES                         C
C       RUN THE TASK BUILDER (TKB <CR>)                              C
C       TKB>MYPROG=MYPROG,LB:[1,1]GGLIB/LB <CR>                      C
C       TKB>/                                                        C
C       ENTER OPTIONS                                                C
C       TKB>ASG=TTn:3           !WHERE n EQUALS GIGI TERMINAL NUMBER C
C       TKB>//                  !  COULD USE TI: INSTEAD             C
C*********************************************************************
C
C
C
      SUBROUTINE GGVERS(IVERS)
C     CALL TO THIS WILL GIVE THE CURRENT VERSION OF THE GGLIB
      IVERS=12
      RETURN
      END
C
C
C
      SUBROUTINE GGON
C     THIS WILL SEND THE ESC Pp SEQUENCE TO THE GIGI TO ENABLE THE
C     GRAPHICS
      BYTE ESC
      ESC=27
      WRITE(3,100)ESC
100   FORMAT('+',1A1,'Pp')
      RETURN
      END
```

```
C
C
C
      SUBROUTINE GGOFF
C     THIS WILL SEND THE ESC ® NEEDED
C      TO TURN OFF THE GIGI GRAPHICS MODE
      BYTE ESC
      ESC=27
      WRITE(3,100)ESC
100   FORMAT('+',1A1,'®')
      RETURN
      END
C
C
C
      SUBROUTINE GGERA
C     ROUTINE TO PERFORM SCREEN ERASE
      WRITE (3,100)
100   FORMAT('+','S(E)')
      RETURN
      END
C
C
C
      SUBROUTINE GGDMP
C     ROUTINE TO PERFORM SCREEN DUMP TO LA34/LA100 PRINTER
      WRITE(3,100)
100   FORMAT('+','S(H)')
      RETURN
      END
C
C
C
      SUBROUTINE GGINIT
C     ROUTINE TO INITIALIZE THE GIGI
      WRITE(3,100)
100   FORMAT('+','W(R,I4,P1,N0,S0,A0)')
      RETURN
      END
C
C
C
      SUBROUTINE GGAXIS(IX,IY,IFX,IFY)
C
C     ROUTINE TO INITIALIZE THE AXIS OF THE GIGI
C     WHERE IX = LOWER LEFT CORNER X VALUE
C           IY = LOWER LEFT CORNER Y VALUE
C           IFX= UPPER RIGHT CORNER X VALUE
C           IFY= UPPER RIGHT CORNER Y VALUE
      WRITE(3,100)IX,IFY,IFX,IY
100   FORMAT('+','S(A[',I5,',',I5,'][',I5,',',I5,'])')
      RETURN
      END
C
```

```
C
C
      SUBROUTINE GGPLT(COLOR,IX,IY,IFLAG)
C  SUBROUTINE TO POSITION GRAPHICS CURSOR ON THE GIGI
C    SET IFLAG TO NUMBER > 0 TO PLOT POINT AND TO 0
C    TO MOVE CURSOR TO POINT WITHOUT PLOTTING POINT
C              COLOR = BYTE variable 0-7 for color
C              IX = Integer value of X
C              IY = Integer value of Y
C              IPT = Integer flag >1 plot a point
      BYTE COLOR
      IF(IFLAG.GT.0)GOTO10
      WRITE(3,100)COLOR,IX,IY
100   FORMAT('+ W(I',I1,')P[',I4,',',I4,']')
      GOTO20
10    WRITE(3,101)COLOR,IX,IY
101   FORMAT('+ W(I',I1,')P[',I4,',',I4,']V[]')
20    CONTINUE
      RETURN
      END
C
C
C
      SUBROUTINE GGPLOT(COLOR,IX,IY,IFLAG)
C     ROUTINE TO ALLOW FOR VARIATION IN SPELLING OF GGPLT ROUTINE
C     ADDED IN VERS 12
      BYTE COLOR
      CALL GGPLT(COLOR,IX,IY,IFLAG)
      RETURN
      END
C
C
C
      SUBROUTINE GGVEC(COLOR,IX,IY)
C  SUBROUTINE TO DRAW A VECTOR ON THE GIGI FROM ITS PRESENT POSITION
C    TO THE IX,IY POSITION IN THE PARAMETER LIST.  USE GGPLT FOR
C    INITIAL COORDINATES IF NEEDED.
C              COLOR = BYTE variable 0-7 for color
C              IX = Integer value of X
C              IY = Integer value of Y
      BYTE COLOR
      WRITE(3,100)COLOR,IX,IY
100   FORMAT('+ W(I',I1,')V[',I4,',',I4,']')
      RETURN
      END
C
C
C
      SUBROUTINE GGBOX(COLOR,IX,IY,IX1,IY1)
C  SUBROUTINE TO DRAW A BOX ON THE GIGI GIVEN THE OPPOSITE COORDINATE
C    PAIRS FOR THE RECTANGLE.
C              COLOR = BYTE variable 0-7 for color
C              IX0 = Integer value of X
C              IY0 = Integer value of Y
```

```
C               IX1 = Integer value of X opposite
C               IY1 = Integer value of Y opposite
C
C       IF THE FILL IS TURNED ON THE BOX WILL BE FILLED AUTOMATICALLY
C
        BYTE COLOR
        CALL GGPLT(COLOR,IX,IY,1)
        CALL GGVEC(COLOR,IX1,IY)
        CALL GGVEC(COLOR,IX1,IY1)
        CALL GGVEC(COLOR,IX,IY1)
        CALL GGVEC(COLOR,IX,IY)
        RETURN
        END
C
C
C
        SUBROUTINE GGCIRC(COLOR,IX,IY,IRAD)
C  SUBROUTINE TO DRAW A CIRCLE AT POINT IX,IY WITH A RADIUS OF IRAD
C               COLOR = BYTE variable 0-7 for color
C               IX = Integer value of X
C               IY = Integer value of Y
C               IRAD = Integer radius of circle
C
C  IF THE FILL IS TURNED ON THE CIRCLE WILL BE FILLED AUTOMATICALLY
C
        BYTE COLOR
        CALL GGPLT(COLOR,IX,IY,0)
        WRITE(3,100)COLOR,IX,IY+IRAD
100     FORMAT('+ W(I',I1,')C[',I4,',',I4,']')
        CALL GGPLT(COLOR,IX,IY,1)               !LEAVE CURSOR AT CENTER
        RETURN
        END
C
C
C
        SUBROUTINE GGTEXT(COLOR,IX,IY,TEXT,ISIZE,ITILT)
C SUBROUTINE TO WRITE TEXT AT IX,IY ON SCREEN
C       Writes text at ix,iy with size and rotation of
C         characters given
C               COLOR = BYTE variable 0-7 for color
C               IX = Integer value of X
C               IY = Integer value of Y
C               TEXT = BYTE array containing 80 char or less
C               ISIZE = Integer value for text size 0-8
C               IROT = Integer value of degress of rotation for
C                       line of text (multiple of 45)
C
C       THIS SUBROUTINE CALLS LENGTH TO DETERMINE
C        THE LENGTH OF THE STRING
C
        BYTE COLOR,TEXT(1)
        N=0
        CALL GGPLT(COLOR,IX,IY,0)
        CALL LENGTH(TEXT,N)
```

```
      WRITE (3,100)ITILT,ISIZE,ITILT,(TEXT(I),I=1,N)
100   FORMAT('+ T(D',I4,')(S',I2,')(D',I4,')',1H',<N>A1,1H')
      RETURN
      END
C
C
C
      SUBROUTINE LENGTH(TEXT,N)
      BYTE TEXT(80)
      IFLAG=0
      DO 20 I=80,1,-1
      IF(TEXT(I).GT.32)IFLAG=1
        N=I
        IF (IFLAG.EQ.0)GOTO20
        GOTO99
20    CONTINUE
99    RETURN
      END
C
C
C
      SUBROUTINE GGFILL(IFLAG)
C     SUBROUTINE TO TURN ON/OFF COLOR FILL CHARACTERISTIC
C       IFLAG=0 NOFILL, IFLAG=1 FILL
C
      WRITE(3,100)IFLAG
100   FORMAT('+','W(S',I1,')')
      RETURN
      END
```

```
      PROGRAM PLOTZ
C
C
C     **6/27/83
C     CHANGED AXIS ROUTINE FOR THREECORNERED ORIGIN**
C
C     VERSION 1.6
C     WRITTEN BY JOHN RICHARDSON
C     APRIL 27, 1983
C
C     SURFACE PLOTTING PROGRAM
C
      DIMENSION IY(50,200),IOUT(200),IOUTY(200)
      DIMENSION IX(200),MASK(800)
      BYTE FNAM(20),DES(40),GON(3),GOFF(2),COLOR
      BYTE BLACK,BLUE,RED,MAGENT,GREEN,CYAN,YELLOW,WHITE,ESC
      INTEGER DELTAX,DELTAY
      COMMON /IAREA/MASK
      DATA FNAM/15*0,'.','D','A','T',0/
      DATA MASK/800*0/,DELTAX/6/,DELTAY/6/
      BLACK=0
      BLUE=1
      RED=2
      MAGENT=3
      GREEN=4
      CYAN=5
      YELLOW=6
      WHITE=7
      COLOR=GREEN
      IXSCLE=3
      ESC=27
      WRITE(5,499)ESC,ESC
499   FORMAT('+',A1,'PrTM1',A1,'®')
C     !SET TERMINAL TO ANSII MODE
      TYPE 500
 500  FORMAT(1X,'INPUT FILE NAME ')
      ACCEPT 501,(FNAM(I),I=1,15)
 501  FORMAT(15A1)
      OPEN(UNIT=1,NAME=FNAM,FORM='UNFORMATTED',TYPE='OLD')
      READ(1),(DES(I),I=1,40),NRUN,NCNTS
     +,((IY(J,K),K=1,NCNTS),J=1,NRUN)
      CLOSE(UNIT=1)
      TYPE 5
5     FORMAT('  REVERSE THE SLICES? (1-YES, 0-NO) ')
      ACCEPT 6,NSLICE
6     FORMAT(I5)
      WRITE(5,61)
61    FORMAT(' SHIFT SUCCESSIVE SLICES (1 = LEFT, -1 = RIGHT) '$)
      READ (5,62)ISHFT
62    FORMAT(I3)
C
C
      WRITE(5,621)
621   FORMAT(' WHAT ARE THE VALUES FOR DELTAX, DELTAY, IXSCLE [I] '$)
```

```
      READ(5,622)DELTAX,DELTAY,IXSCLE
622   FORMAT(3I4)
C
C
      WRITE(5,623)
623   FORMAT('  WHAT IS CROSS HATCH INTERVAL [I] '$)
      READ(5,624)NXHTC
624   FORMAT(I3)
C
C
      DELTAX=DELTAX*ISHFT
171   CALL GGON
      CALL GGINIT
      CALL GGAXIS(0,0,767,479)
      CALL GGERA
C     CALL GGBOX(7,0,0,767,479)
C
C     SET UP DATA POINTS FOR X AXIS
C
      DO 19 NPOINT=1,NCNTS
      IX(NPOINT)=NPOINT*IXSCLE
19    CONTINUE
      nline=1
      DO 11 NPOINT=1,NCNTS
      IOUTY(NPOINT)=IY(IABS(NLINE-NSLICE*NRUN),NPOINT)/4
 11   CONTINUE

      DO 20 NLINE=1,NRUN,1
      DO 10 NPOINT=1,NCNTS
      IOUT(NPOINT)=IY(IABS(NLINE-NSLICE*NRUN),NPOINT)/4
 10   CONTINUE
      CALL GG3DX(COLOR,IX,IOUT,IOUTY,NCNTS,NLINE,DELTAX,DELTAY,NXHTC)
      DO 30 NPOINT=1,NCNTS
      IOUTY(NPOINT)=IOUT(NPOINT)
30    CONTINUE
 20   CONTINUE
      CALL AXIS(COLOR,NRUN,NCNTS,DELTAX,DELTAY,IXSCLE)
C
C
      CALL GGOFF
      WRITE(5,2000)ESC,FNAM
2000  FORMAT('+',A1,'[H'/' ',20A1)
      WRITE(5,2001)ESC
2001  FORMAT('+',A1,'[H 0-QUIT, 1-SCREENDUMP, 2-SCRDMP NO LABEL '$)
      READ(5,2002)IANS
2002  FORMAT(I2)
      IF(IANS.EQ.0)GOTO2100
      WRITE(5,2004)ESC
2004  FORMAT('+',A1,'[H',80X)
      IF (IANS.NE.2)GOTO 20035
      WRITE(5,2005)ESC
2005  FORMAT('+'A1,'[H',80X/80X)
20035 CALL GGON
      WRITE(5,2003)
```

```
2003  FORMAT('  S(H)')
      CALL GGOFF
2100  END
C
C
C
C
      SUBROUTINE GG3DX(COLOR,IX,IY,IYX,NPNTS,N,DELTAX,OELTAY,NXHTC)
      BYTE COLOR
      OIMENSION IX(1),IY(1),MASK(1),IYX(1)
      COMMON /IAREA/MASK
      INTEGER OELTAY,OELTAX
      IXOFF=200
      IF(OELTAX.LT.0)IXOFF=50
      IF(N.NE.1)GOTO10
C
C     SET UP MASK FOR FIRST SLICE
      DO 5 I=1,NPNTS
      MASK(IX(I)+(IXOFF-N*DELTAX))=IY(I)+N*OELTAY
5     CONTINUE
C
C
10    CONTINUE
      OO 20 I=1,NPNTS
      IXOUT=IX(I)+(IXOFF-N*OELTAX)
      IYOUT=IY(I)+N*OELTAY+20
      IF(IYOUT.GE.MASK(IXOUT))GOTO50
      GOTO 20
50    MASK(IXOUT)=IYOUT
      CALL GGPLT(COLOR,IXOUT,IYOUT,1)
              IF(N.LE.1)GOTO20
              IF(I.EQ.1)GOTO19
              IF(IMOO(I,NXHTC).NE.0)GOTO20
19            IX2=IXOUT+OELTAX
              IY2=IYX(I)+(N-1)*DELTAY+20
              IF(DELTAX.LT.0)GOTO190
              IF(IY2.LT.MASK(IX2))GOTO20
190           CALL GGVEC(COLOR,IX2,IY2)
20    CONTINUE
      GOTO 33
C     IF(N.EQ.1)GOTO33
C     M1=MASK(IXOFF-(N-1)*DELTAX)
C     DO 33 I=1 ,DELTAX
C     MASK(IXOFF-(N*DELTAX)+I)=M1
33    CONTINUE
      RETURN
      END
C
C
      SUBROUTINE AXIS(COLOR,NLINE,NPNTS,DELTAX,DELTAY,IXSCLE)
      BYTE COLOR
      INTEGER OELTAX,DELTAY,MASK(1)
      INTEGER X0,Y0,X1,Y1,X2,Y2,X3,Y3,X4,Y4,X5,Y5,X6,Y6,XORG,YORG
      INTEGER X7,Y7
```

```
      COMMON /IAREA/MASK
      IXOFF=200
      IF(DELTAX.LT.0)IXOFF=50
      ISIGN=DELTAX/IABS(DELTAX)
C
C
      X0=IXOFF
      Y0=20
C
      X1=IXOFF+IXSCLE*NPNTS
      Y1=20
C
      X2=IXOFF-NLINE*DELTAX
      Y2=20+NLINE*DELTAY
C
      X3=X2
      Y3=Y2+250
C
      X4=X2+NPNTS*IXSCLE
      Y4=Y2
C
      X5=X0
      Y5=Y0+250
C
      X6=X4
      Y6=Y3
C
      XORG=X2
      YORG=Y2
C
      X7=X1
      Y7=Y5
C
      CALL GGPLT(COLOR,X6,Y6,1)
      IF(DELTAX.LT.0)GOTO15
      IYTEMP=MASK(X4)
      CALL GGVEC(COLOR,X6,IYTEMP)
      GOTO16
15    CALL GGVEC(COLOR,X4,Y4)
      CALL GGVEC(COLOR,X1,Y1)
16    CALL GGPLT(COLOR,X1,Y1,1)
      CALL GGVEC(COLOR,X0,Y0)
      IF (DELTAX.GT.0)CALL GGVEC(COLOR,X2,Y2)
      CALL GGPLT(COLOR,X2,Y2,1)
161   IF(DELTAX.GT.0)GOTO191
      IYTEMP=MASK(X2)
      CALL GGPLT(COLOR,X2,IYTEMP,1)
191   CALL GGVEC(COLOR,X3,Y3)
      IF(ISIGN.GT.0)GOTO200
C     SURFACE FOR LEFT SHIFT
      CALL GGPLT(COLOR,X3,Y3,1)
      CALL GGVEC(COLOR,X5,Y5)
      CALL GGVEC(COLOR,X0,Y0)
199   GOTO201
```

```
C       SURFACE FOR RIGHT SHIFT
200     CALL GGPLT(COLOR,X6,Y6,1)
        CALL GGVEC(COLOR,X7,Y7)
        CALL GGVEC(COLOR,X1,Y1)
201     CONTINUE
C
C       VERTICAL AXIS TICS
C
        DO 20 I=0,10
        IY0=(I*25)+Y2
        IF(DELTAX.LT.0)GOTO19
        CALL GGPLT(COLOR,X2,IY0,1)
        CALL GGVEC(COLOR,X2-6,IY0)
        GOTO20
19      CALL GGPLT(COLOR,X4,IY0,1)
        CALL GGVEC(COLOR,X4+6,IY0)
20      CONTINUE
C
C       HORIZONTAL AXIS TICS
C
        DO 25 I=0,10
        IX0=I*NPNTS*IXSCLE/10+X0
        CALL GGPLT(COLOR,IX0,Y0,1)
        CALL GGVEC(COLOR,IX0,Y0-6)
25      CONTINUE
C
C       ANGLE AXIS TICS
C
        ZLINE=NLINE
        DO 35 ZI=0.,ZLINE,ZLINE/10.
        IF(DELTAX.LT.0)GOTO27
        IX0=X0-DELTAX*ZI
        IY0=Y0+DELTAY*ZI
        GOTO28
27      IX0=X1-DELTAX*ZI
        IY0=Y1+DELTAY*ZI
28      CONTINUE
        IC4=ISIGN*6
        CALL GGPLT(COLOR,IX0,IY0,1)
        CALL GGVEC(COLOR,IX0-IC4,IY0-6)
35      CONTINUE
C
C       BACK AXIS LINE
C
C       CALL GGPLT(COLOR,X2,Y2,1)
C       CALL GGVEC(COLOR,X4,Y4)
C
C       TOP AXIS LINE
C
        CALL GGPLT(COLOR,X3,Y3,1)
        CALL GGVEC(COLOR,X6,Y6)
        RETURN
        END
```

```
1 '   PROGRAM MEASURE3 WRITTEN BY JOHN R. RICHARDSON
2 VERSION=2!
3 '   VERSION 1.0 BASELINE SET 6/1/85
5 '   MAIN PROGRAM BEGINS AT LINE 1000
6 '   VERSION 1.5 6/3/85
7 '        CLEANED UP OLD FORTRAN COOE, ADDED OOUBLE OUTPUT FILE MOOE
8 '        SAVE TRUE DIGITIZER VALUES FOR PLOTTER FILE OUTPUT
9 '        CALCULATE AREAS BASED ON SCALED OATA
10 ' VERSION 1.6 6/7/85
11 '      FIXED ERROR IF NO FILES OF B DRIVE,
12 '      CHANGED OATA ARRANGEMENT IN OUTPUT FILES
13 ' VERSION 1.7 6/24/85
14 '   ADOED ERROR OUTPUT ROUTINE FOR ERRORS OTHER THAN NO FILES
15 ' VERSION 2.0 ADOED SCALE3 SUB FOR DIFFERENT XSCALE AND YSCALE
16 '    7/2/85
99 '******************************************************************
100 ' SUBROUTINE DIGINI (LINE 3000-3490) OPENS OIGITIZER
110 '  AND SETS INITIAL  PARAMETERS FOR PROGRAM
130 ' SUBROUTINE STREAM MOOE (3800-3899) TURNS ON STREAM MOOE
150 ' SUBROUTINE POINT MODE (3900-3999) TURNS ON POINT MOOE
170 ' SUBROUTINE FILE HANOLER (4000-4220) OPENS OATA FILE FOR OUTPUT
190 ' SUBROUTINE SCALE2 (5000-5610) HANOLES SETTING UP USER
200 '    COORDINATES ANO ORIGINS AND OFFSETS
220 ' SUBROUTINE OELAY (6000-6010) ARE TIMING ROUTINES THAT
230 '  MAY BE NEEDED FOR  SENOING SETUP INFORMATION TO OIGITIZER
250 ' SUB INPUT  (8000-8070) GETS OATA SENT FROM OIGITIZER
270 ' SUB OIGURU (9000-9070) SCALES OIGITIZER INPUT TO REAL WORLO
290 '    COORDINATES
300 ' SUBROUTINE AREAP (1660-2030) GETS INPUT POINTS FOR AN AREA
330 ' SUBROUTINE AREAX (2070-2580) CALCULATES THE AREA
350 ' SUBROUTINE PERIX (2610-2810) CALCULATE THE CLOSED AND OPEN
370 '    PERIMETERS FROM A SET OF GIVEN POINTS
1000 '****************************************************************
1010 '************************ MAIN PROGRAM START ****************
1020 '****************************************************************
1040 ON ERROR GOTO 20000
1060 CLS:PRINT:PRINT:PRINT:PRINT
1070 PRINT "AREA MEASUREMENT PROGRAM VERSION ";VERSION
1120 GOSUB 4000:' CALL FILE HANDLER
1130 GOSUB 3000:' CALL OIGINI
1140 GOSUB 5000:' CALL SCALE2
1260 'CONTINUE
1270 GOSUB 1660:' CALL AREAP (X,Y,AREA,NPOINT,IERR,RESOL)
1280  IF (IERR=0) THEN GOTO 1290 ELSE PRINT "ERROR ";IERR;"
     HAS OCCURRED NOT ENOUGH POINTS FOR AN AREA":GOTO 1270
1290 '
1340 GOSUB 2070:' CALL AREAX(X,Y,AREA,NPOINT)
1350 GOSUB 2610:' CALL PERIX(X,Y,PERI1,PERI2,NPOINT)
1351 AREA=AREAIO
1370 PRINT " THE MEASURED AREA IS [";AREAIO;"] FOR ";NPOINT;" POINTS"
1380 PRINT "  CLOSED PERIMETER=    ";PERI2
1390 PRINT "  OPEN   PERIMETER=    ";PERI1
1400 PERIOUT=PERI2
1410 PRINT BELL$;" KEEP THIS AREA OR RE-MEASURE [K or R] ";
```

```
1420 INPUT ANS$
1440  IF (ANS$ ="R")GOTO 1260
1480 PRINT #2,XT(1),YT(1),PENOUM;AREA;PERIOUT;NPOINT
1481 PRINT #3,AREA;PERIOUT
1490 PRINT #2,XT(1),YT(1),PENUP
1500 FOR I=2 TO NPOINT
1510 PRINT #2,XT(I),YT(I),PENDWN
1520 NEXT I:'200       CONTINUE
1525 IF WET5=99 THEN 1590
1530 PRINT #2,XT(1),YT(1),PENOWN
1590 PRINT " OO YOU WANT TO INPUT ANOTHER AREA (Y OR N) ";
1600 INPUT ANS$
1620  IF (ANS$ = "Y") GOTO 1260
1630  CLOSE:PRINT "TYPE SYSTEM TO EXIT FROM BASIC OR RUN TO RERUN":END
1640 '*****************************************************************
1641 '************************* END OF MAIN PROGRAM *****************
1642 '*****************************************************************
1660 PRINT "SUBROUTINE AREAP":IERR=0
     :' SUBROUTINE AREAP(X,Y,AREA,NPOINT,IERR,RESOL)
1700 IERR=0
1710 NPOINT=0
1720  AREA=0
1740 PRINT " ENTER FIRST POINT BY PRESSING THE '1' KEY  "
1745 PRINT " ENTER REMAINING POINTS BY PRESSING ANY KEY BUT '2'"
1750 PRINT "           THEN QUIT ENTERING POINTS BY PRESSING '2' "
1760 GOSUB 9000:' CALL DIGURU (XIN,YIN,CODE)
1770  XOLD=XIN
1780  YOLD=YIN
1790  IF (COOE$ <> "1") GOTO 1760
1800 NPOINT=1
1810   X(NPOINT)=XOLD
1811   XT(NPOINT)=XTRUE
1820   Y(NPOINT)=YOLD
1821   YT(NPOINT)=YTRUE
1830   IF (COOE$ = "2") GOTO 1950
1840 GOSUB 9000:'200       CALL DIGURU (XIN,YIN,CODE)
1850   IF (CODE$ = "2" ) GOTO 1950
1870   NPOINT=NPOINT+1
1880   X(NPOINT)=XIN
1881   XT(NPOINT)=XTRUE
1890   Y(NPOINT)=YIN
1891   YT(NPOINT)=YTRUE
1900   XOLD=XIN
1910   YOLD=YIN
1930 PRINT XIN,YIN,"CODE =";CODE$:BEEP
1940   GOTO 1840
1950  IF (NPOINT < 3) THEN IERR =1: '300
1970   IF (IERR <>  0)THEN RETURN
2020   IERR=0
2025 'GOSUB 3900
2030   RETURN
2070 PRINT " SUBROUTINE AREAX(X,Y,AREAIO,NPOINT)"
2130 PRINT   " **** OIGITIZER AREA CALCULATION ****"
2140  NUMPNT=0:'200
```

```
2150  A1=0!
2160  A2=0!
2170  AREAIO=0!
2180  NUMPNT=NUMPNT+1
2190 'C READ FIRST PAIR
2200   XF=X(NUMPNT)
2210   YF=Y(NUMPNT)
2220         XP=XF
2230         YP=YF
2240 '300        CONTINUE
2250 'C
2260  NUMPNT=NUMPNT+1
2270 XC=X(NUMPNT)
2280   YC=Y(NUMPNT)
2290         A1=A1+(XP*YC)
2300         XP=XC
2310   IF(NUMPNT =  NPOINT)GOTO 2330
2320   GOTO 2240
2330   IF(NUMPNT >  2)GOTO 2370:'400
2340 '       WRITE(LUNO,401)
2350 PRINT  " ?NOT ENOUGH DATA POINTS FOR AREA CALCULATION"
2360         RETURN
2370   A1=A1+(XC*YF):'450
2380   NUMPNT=1
2390   XF=X(NUMPNT)
2400   YF=Y(NUMPNT)
2410         XP=XF
2420         YP=YF
2430             NUMPNT=NUMPNT+1:'500
2440   YC=Y(NUMPNT)
2450   XC=X(NUMPNT)
2460         A2=A2+(YP*XC)
2470         YP=YC
2480   IF (NUMPNT =  NPOINT)GOTO 2500
2490         GOTO 2430
2500  A2=A2+(YC*XF):'600
2510         AREAIO=ABS((A1-A2)*.5)
2520         RETURN
2530 '700    AREAIO=0.
2540 '       RETURN
2550 '800        CONTINUE
2560 '       AREAIO=0.
2570         RETURN
2580 '       END
2590 'C
2600 'C
2610 PRINT "' SUBROUTINE PERIX(X,Y,PERI1,PERI2,NPOINT)"
2620 '  DIMENSION X(1),Y(1)
2630   PERI1=0!
2640   PERI2=0!
2650   NUMPNT=1
2660   XIN=X(1)
2670   YIN=Y(1)
2680   XL=XIN
```

```
2690   YL=YIN
2700   NUMPNT=NUMPNT+1:'100
2710   XN=X(NUMPNT)
2720   YN=Y(NUMPNT)
2730   PERI1=PERI1+FNRDIST(XN,YN,XL,YL)
2740   XL=XN
2750   YL=YN
2760   IF (NUMPNT =  NPOINT)GOTO 2780
2770   GOTO 2700
2780           PERI2=FNRDIST (XIN,YIN,XL,YL):'300
2790   PERI2=PERI2+PERI1
2800   RETURN
2810 '  END
2820 '
2830 '
3000 PRINT "SUBROUTINE DIGINI"'    SUBROUTINE DIGINI
3001 LCB=13
3002 DEF FNRDIST(X1,Y1,X2,Y2)=ABS((X1-X2)©2+(Y1-Y2)©2)©.5
3003 DEF FNANGLER(X1,Y1,X2,Y2)=ATN((Y2-Y1)/(X2-X1))
     +(SGN(ABS(X2-X1))-SGN((X2-X1)))*1.570796
3005 PRINT "INITIALIZATION SEQUENCE FOR DIGITIZER":BEEP
3006 PRINT" PLEASE MAKE SURE DIGITIZER IS ON"
3007 INPUT " HIT RETURN WHEN READY ",DUM$
3008 DIM X(1000),Y(1000),XT(1000),YT(1000)
3009 PENUP=3:PENDWN=2:PENDUM=6:BELL$=CHR$(7)
3010 OPEN"COM1:9600,E,7,2,RS,CS,DS,CD" AS #1:'OPEN AUX PORT FOR I/O
3011 CLS
3020 LD$="#]":QT$="/"
3025 PRINT #1,"#]L":PRINT " DIGITIZER BEING RESET ":GOSUB 6005
3030 PRINT #1,"#](":'SET RESOLUTION TO .001
3031 GOSUB 6001
3040 PRINT #1,"#]6":'SET RATE TO 2/SEC
3041 GOSUB 6001
3050 PRINT #1,"#]'02":'SET INCREMENT TO .01
3051 GOSUB 6001
3060 'PRINT #1,"#]M":' TURN ON INCREMENTAL MODE
3061 'GOSUB 6001
3070 'PRINT #1,"#]J":' TURN ON STREAM MODE
3071 'GOSUB 6001
3080 PRINT #1,"#]9":' SET SERIAL TAG AS LAST CHARACTER
3081 GOSUB 6001
3090 PRINT #1,"#]>":' SET NO FIELD DELIMITERS
3091 GOSUB 6001
3100 PRINT #1,"#]I":' RESET FOR POINT MODE FOR BEGINNING SETUP
3110 PRINT #1,"#]/":' SEND END OF REMOTE FORMATTING
3111 GOSUB 6001
3310         XSCALE=1!:'USER X AXIS SCALE FACTOR
3320         XOFF=0!:'  USER X AXIS OFFSET
3330         YSCALE=1!:'USER Y AXIS SCALE FACTOR
3340         YOFF=0!:   'USER Y AXIS OFFSET
3350         ANGLE=0!:' USER SKEW CORRECTION FACTOR
3360 '       XROUND=0.
3370 '       YROUND=0.
3380         UXSCAL=1!:'USER PLOTTER X SCALE FACTOR
```

```
3390         UYSCAL=1!:'USER PLOTTER Y SCALE FACTOR
3400         UROT=0!  :'USER PLOTTER ROTATIDN ANGLE
3410 '       ARRLEN=.15
3420 '       ARRWID=.07
3430 '       ARROFF=.03
3440 '       IARRTY=3
3450 '       PDLEN=.1
3460 '       PULEN=.05
3470         XLAST=0!:'LAST X COORD CALCULATED
3480         YLAST=0!:'LAST Y COORD CALCULATED
3490 RETURN
3500 'CLOSE FILE THEN REOPEN IT
3510 CLOSE #1
3520 OPEN"CDM1:9600,E,7,2,RS,CS,DS,CD" AS #1:'OPEN AUX PORT FOR I/O
3530 RETURN
3800 PRINT "STREAM MDDE SUBROUTINE"
3810 PRINT #1,"#]J":' TURN DN STREAM MDDE
3811 GOSUB 6001
3820 PRINT #1,"#]M":' TURN DN INCREMENTAL MODE
3821 GOSUB 6001
3899 RETURN
3900 PRINT " SUBROUTINE FOR SETTING POINT MDDE"
3910 PRINT #1,"#]I":' RESET FDR PDINT MDDE FOR BEGINNING SETUP
3911 GOSUB 6001
3999 RETURN
4000 PRINT "FILE HANDLING SUBROUTINE":' SUBROUTINE FOR FILE HANDLING
4004 PRINT "CURRENT DATA FILES: ":PRINT
4005  FILES "B:*.*"
4006 PRINT:PRINT:PRINT:
4010 'PRINT "FILE HANDLING"
4020 PRINT "WDULD YOU LIKE TO OPEN A NEW FILE DR APPEND TO AN EXISTING"
4030 INPUT "   FILE (1-NEW, 2-OLD)",FILEMODE
4040 IF FILEMODE <1 OR FILEMODE >2 THEN 4020
4050 IF FILEMODE =2 THEN 4100
4060 INPUT "WHAT IS THE NAME FDR THE FILE (1-8 CHARACTERS) ";FILENAME$
4061 IF LEN (FILENAME$)>8 THEN 4060
4062 IF INSTR(FILENAME$,":") <>0 THEN PRINT "INPUT FILENAME
     DNLY WITHOUT DRIVE SPECIFIER":GOTD 4000
4070 NTEMP=INSTR(FILENAME$,".")
4075 IF NTEMP=0 THEN 4085
4078 NLEN=LEN(FILENAME$)
4080 FILENAME$=MID$(FILENAME$,1,NTEMP-1)
4085 FILENAME$="B:"+FILENAME$
4090 DPEN "D",2,FILENAME$+".DAT"
4091 DPEN "D",3,FILENAME$+".PRN"
4093 INPUT "WHAT IS DESCRIPTIDN DF THIS DATA SET",DESC$
4094 PRINT #3,CHR$(34)+DESC$
4095 GOTD 4220
4100 'OPEN FDR APPEND
4110 INPUT "WHAT IS THE NAME OF THE EXISTING FILE ",FILENAME$
4120 IF LEN(FILENAME$)>8 THEN 4110
4130 IF INSTR(FILENAME$,":") <>0 THEN PRINT "INPUT FILENAME
     ONLY WITHDUT DRIVE SPECIFIER":GOTD 4100
4140 NTEMP=INSTR(FILENAME$,".")
```

```
4150 IF NTEMP=0 THEN 4200
4160 NLEN=LEN(FILENAME$)
4170 FILENAME$=MID$(FILENAME$,1,NTEMP-1)
4200 FILENAME$="B:"+FILENAME$
4202 OPEN "I",3,FILENAME$+".PRN"
4204 LINE INPUT #3,DUM$:PRINT:PRINT DUM$:PRINT:PRINT
4206 CLOSE #3
4210 OPEN"A",2,FILENAME$+".DAT"
4211 OPEN"A",3,FILENAME$+".PRN"
4220 'INPUT "BASIN NUMBER = ",WET1
4250 RETURN
5000 'PRINT"SUBROUTINE SCALE3" : '      SUBROUTINE SCALE3
5030 GOSUB 3900: ' GO SET POINT MODE FIRST !
5040 PRINT " ****** DIGITIZER THREE-POINT SCALING ******"
5050 PRINT :PRINT:PRINT :BEEP:GOSUB 6001
5060 PRINT "  DIGITIZE THE ORIGIN OF THE GRAPH >>":BEEP
5070 GOSUB 8000:XORG=XIN:YORG=YIN:'      CALL DIGDRU(XORG,YORG,IBTN)
5080    IF(VAL(CODE$)=10)GOTO 5530
5100 PRINT " DIGITIZE ANY OTHER KNOWN"
5110 PRINT "  POINT ON THE SAME HORIZONTAL (X-AXIS) LINE>>"
5120 GOSUB 8000:XHZ=XIN:YDUMM=YIN:'      CALL DIGDRU(XHZ,YHZ,IBTN)
5130   IF(VAL(CODE$)=  10)THEN RETURN
5140         XSCALE=1!
5150         XOFF=0!
5160         YSCALE=1!
5170         YOFF=0!
5180         ANGLE=0!
5190         XROUND=0!
5200         YROUND=0!
5210         XD=FNRDIST(XORG,YORG,XHZ,YDUMM)
5220         IF(XD =  0!)THEN RETURN:'GOSUB 3800:RETURN:'STREAM MODE
5240 'PRINT " TWO-POINT X DISTANCE IN DIGITIZER REAL UNITS: ";XD
5242 PRINT "DIGITIZE A THIRD KNOWN POINT ON THE VERTICAL (Y-AXIS) LINE"
5244 GOSUB 8000:XDUMM=XIN:YHZ=YIN
5246 ANG1=FNANGLER(XORG,YORG,XHZ,YDUMM)
5247 ANG2=FNANGLER(XORG,YORG,XDUMM,YHZ)
5248 YANG=1.570796-(ANG2-ANG1)
5249 YD=FNRDIST(XORG,YORG,XDUMM,YHZ)*COS(YANG)
5250 IF YD=0 THEN RETURN
5252 PRINT "X-DISTANCE= ";XD;"  Y-DISTANCE= ";YD
5260 PRINT " ENTER USER COORDINATES"
5270 PRINT " OF THE FIRST POINT (REAL) [0.0,0.0]: ";
5280 INPUT X1U,Y1U
5290 '5      FORMAT(2F10.0)
5300         XDEF=XD+X1U:YDEF=YD+Y1U
5310 '       WRITE(LUNO,6)XDEF
5320 PRINT  " ENTER USER X COORDINATE"
5330 PRINT " OF THE SECOND POINT (REAL) ";XDEF
5340 INPUT X2U
5350  IF(X2U =  0!)THEN X2U=XDEF
5351 PRINT " ENTER USER Y COORDINATE"
5352 PRINT " OF THE THIRD POINT (REAL) ";YDEF
5353 INPUT Y3U
5360        XU=X2U-X1U
```

```
5365          YU=Y3U-Y1U
5370          ANGLE=ANG1
5380          IF(XU <> 0!)THEN XSCALE=XU/XD
5390          IF(YU <> 0)THEN YSCALE=YU/YD
5400          IF(X1U =  0! AND Y1U =  0!)GOTD 5510
5402          X1U=X1U/XSCALE:Y1U=Y1U/YSCALE
5410          ANGLU=FNANGLER(0!,0!,X1U,Y1U)
5420          ANGLU=ANGLE+ANGLU
5430          DISTU=FNRDIST(0!,0!,X1U,Y1U)
5440 '         DISTX=DISTU/XSCALE
5450 '        DISTY=DISTU/YSCALE
5460          XROT=DISTU*CDS(ANGLU)
5470          YRÓT=DISTU*SIN(ANGLU)
5480          XDFF=XDRG-XROT
5490          YDFF=YDRG-YROT
5500          GOTO 5530
5510          XOFF=XDRG:'100
5520          YDFF=YDRG
5530 '200     WRITE(LUNO,201)
5540 PRINT " ENTER X-AXIS ROUNDOFF (REAL) [0.0]: ";
5550 INPUT XROUND
5560 '202     FORMAT(F6.0)
5570 '        WRITE(LUND,203)
5580 PRINT " ENTER Y-AXIS ROUNDDFF (REAL) [0.0]: ";
5590 INPUT YROUND
5600 RETURN:'GOSUB 3800:RETURN :'RESET STREAM MODE FIRST!
5610 '        END
6000 ' TIMER LOOPS
6001 BEEP :FOR IDUM=1 TO 375 :NEXT IDUM:PRINT TIME$:RETURN:'1 SEC
6002 BEEP :FOR IDUM=1 TO 750 :NEXT IDUM:PRINT TIME$:RETURN:'2 SEC
6003 BEEP :FOR IDUM=1 TO 1125:NEXT IDUM:PRINT TIME$:RETURN:'3 SEC
6005 BEEP :FOR IDUM=1 TD 1875:NEXT IDUM:PRINT TIME$:RETURN:'5 SEC
6010 BEEP :FOR IDUM=1 TO 3750:NEXT IDUM:PRINT TIME$:RETURN:'10SEC
8000 REM ++++++ GET INPUT FROM CDM BUFFER ++++++++
8010 WHILE LDC(1) < LCB
8020 WEND
8030 'IF LDF(1) < 24 THEN BEEP:BEEP: BEEP
8040 DZ$=INPUT$(LCB,#1)
8041 'PRINT DZ$
8050 X$=LEFT$(DZ$,5) : Y$=MID$(DZ$,6,5) : CODE$= MID$(DZ$,11,1)
8060 XIN=VAL(X$)/1000 : YIN=VAL(Y$)/1000
8061 'PRINT XIN,YIN,CDDE$:BEEP
8070 RETURN
9000 ' SUBROUTINE DIGURU(X,Y,IBTN)
9010 GDSUB 8000
9020 DISTU=FNRDIST(XDFF,YOFF,XIN,YIN)
9030 ANGU=FNANGLER(XDFF,YDFF,XIN,YIN)-ANGLE
9040 XIN=DISTU*CDS(ANGU)*XSCALE
9050 YIN=DISTU*SIN(ANGU)*YSCALE
9055 XTRUE=XIN/XSCALE:YTRUE=YIN/XSCALE
9070 RETURN
20000 IF ERR=53 AND ERL=4005 THEN PRINT "ND FILES DN B:":RESUME 4006
20030 PRINT "ERROR NUMBER ";ERR;" HAS DCCURRED AT LINE ";ERL
```

```
C
C       PULSING MODEL GIGI VERSION
C       MDDIFIED TO WRITE DATA FILE FOR 3-D GRAPHICS PROGRAM
C
C       PULSEGGM.FTN VERSIDN
C       BASELINE MODEL 2.0 PREVIDUS TO AUG 29,1984
C       VERS 2.1 CHANGED FORMAT OF HARDCDPY PRINTOUT OF VARIABLES
C
C       VERS 2.11 ADDED TOTALS AND DESCRIPTION TD DUTPUT LIST
C
C       VERS 2.12 ADDED K8 TO DUTPUT LIST
C
C       VERS 2.121 (1/24/85) ADDED TRACKING COEFFICIENTS DN K2,K9,K11
C          AND CHANGED FDRMAT 11003 FOR VARS(IVAL) FROM F6.1 TO G15.4
        PROGRAM PULSE
        BYTE XTEXT(80),DES(40),YTEXT(80)
        DIMENSION VARS(20),ALPHA(20)
        DIMENSION FILE(3)
        REAL M1,M2,M3,M4,M9,K10,K11,K12,K13
        REAL K1,K2,K3,K4,K5,K6,K7,K8,K9,J,J0,JNDRM
        EQUIVALENCE (VARS(1),K1),
     +  (VARS(2),K2),
     +  (VARS(3),K3),
     +  (VARS(4),K4),
     +  (VARS(5),K5),
     +  (VARS(6),K6),
     +  (VARS(7),K7),
     +  (VARS(8),K8),
     +  (VARS(9),K9),
     +  (VARS(10),K10),
     +  (VARS(11),K11),
     +  (VARS(12),K12),
     +  (VARS(13),K13),
     +  (VARS(14),XJ0INI),
     +  (VARS(15),Q1IC),
     +  (VARS(16),Q2IC),
     +  (VARS(17),Q3IC),
     +  (VARS(18),Q4IC)
        VIRTUAL IY(6,25,180)

        DATA FILE/3*'    '/
        DATA XTEXT/' ','P','u','l','s','e',' ','M','o','d','e'
     +,'l',' ',67*0/
        DATA DES/40*0/
        DATA YTEXT/80*0/
        DATA ALPHA/'K1  ','K2  ','K3  ','K4  ','K5  ','K6  ','K7  '
     +     ,'K8  ','K9  ','K10 ','K11 ','K12 ','K13 ','J0IN','Q1IC'
     +     ,'Q2IC','Q3IC','Q4IC',2*'    '/
        FT1(A,B)=ABS(AINT(A/B)-A/B)
        VERS=2.121                  !9/7/84 ; 1/24/85
        WRITE(5,100)
100     FORMAT('  WHAT IS THE DATA FILE FOR THIS MDDEL RUN ?')
        READ(5,101)(FILE(I),I=1,3)
101     FDRMAT(3A4)
```

```
      WRITE(5,1011)FILE
1011  FORMAT(1X,3A4)
C     WRITE(5,1016)
C1016 FORMAT(' DO YOU WANT HARDCOPY (1-YES, 0-NO) '$)
C     READ(5,1017)ICOPY
      ICOPY=0
C1017 FORMAT(I2)
C     WRITE (5,1018)
C1018 FORMAT(' WHICH Q TO SAVE (1,2,3,4,5=JR,6=%POW USED)'$)
C     READ (5,1019)IQSAV
      IQSAV=1
C1019 FORMAT(I3)
C     WRITE(5,1020)
C1020 FORMAT(' DO YOU WANT TO PLOT THE GRAPHS (1-YES, 0-NO)'$)
C     READ(5,1021)IPLOT
      IPLOT=0
C1021 FORMAT(I1)
C     WRITE(5,99)
C99   FORMAT(' HOW LONG TO RUN? ')
C     READ(5,98)TIME
C98   FORMAT(G6.0)
      CALL ASSIGN(1,FILE)
      READ(1)E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,E11,E12,E13,E14,E15,
C     COEFFICIENTS ***********************************************
     +NUM,K1,K2,K3,K4,K5,K6,K7,K8,K9,K10,K11,K12,K13
     +,XJ0INI,Q1,Q2,Q3,Q4
C     INITIAL CONDITIONS*******************************************
      CLOSE (UNIT=1)
      Q1IC=Q1
      Q2IC=Q2
      Q3IC=Q3
      Q4IC=Q4
C***********************************************************
C
C
      WRITE(5,1012)K1,K10,K2,K11,K3,K12,K4,K13,K5,XJ0INI,K6,Q1,
     +K7,Q2,K8,Q3,K9,Q4
1012  FORMAT(1X,'1-K1 ',G12.6,'      10-K10',G12.6/
     +1X,'2-K2 ',G12.6,'      11-K11',G12.6/
     +1X,'3-K3 ',G12.6,'      12-K12',G12.6/
     +1X,'4-K4 ',G12.6,'      13-K13',G12.6/
     +1X,'5-K5 ',G12.6,'      14-XJ0INI',G12.6/
     +1X,'6-K6 ',G12.6,'      15-Q1IC',G12.6/
     +1X,'7-K7 ',G12.6,'      16-Q2IC',G12.6/
     +1X,'8-K8 ',G12.6,'      17-Q3IC',G12.6/
     +1X,'9-K9 ',G12.6,'      18-Q4IC',G12.6/
     +1X,' INPUT VARIABLE NUMBER TO VARY => '$)
      READ(5,1013)IVAL
1013  FORMAT(I2)
      WRITE (5,1014)ALPHA(IVAL),VARS(IVAL)
1014  FORMAT(' VARIABLE ',A4,' = ',G12.6/
     +' HOW MUCH TO INCREMENT? '$)
      READ(5,1015)XINC
1015  FORMAT(G15.6)
```

```
C
C
C
C*******************************************************
      CALL ASSIGN (4,'TT0:')
      IF (IPLOT.EQ.0)GOTO499
      CALL GGON
      CALL GGINIT
      CALL GGAXIS(0,0,767,479)
499   Q1IC=Q1
      Q2IC=Q2
      Q3IC=Q3
      Q4IC=Q4
      NSLICE=25
      NCNTS=150
      NRUN=0
500   CONTINUE
C     J0=XJ0INI+NRUN*4.
      IF(NRUN.EQ.0)GOTO501
      VARS(IVAL)=VARS(IVAL)+XINC      !INCREMENT VALUE WE ARE VARYING
501   NRUN=NRUN+1
      J0=XJ0INI
      J=J0/(1+K13*Q1*Q4)      !GIVE JR (J) INITIAL VALUE
      T=0.
C**********************************************************
C     SET K VALUES TO TRACK FOR MULTIRUN MODEL
C
      K3=.1*K2
      K4=.9*K2
C
      K7=.1*K9
      K8=.9*K9
C
      K5=.1*K11
      K6=.9*K11
C**********************************************************
      Q1=Q1IC
      Q2=Q2IC
      Q3=Q3IC
      Q4=Q4IC
      EUSED=0.0
      M1=0.
      M2=0.
      M3=0.
      M4=0.
      R1=0.
      R2=0.
      R3=0.
      R4=0.
      R5=0.
      R6=0.
      R7=0.
      R8=0.
      R9=0.
```

```
      R10=0.
      R11=0.
      R12=0.
      EUSED=0.0
      PAVAIL=0.0
C
C     WRITE(5,1081)
C1081 FDRMAT('  SCALE FACTDR FDR Q2--200. DR 1000.--[R]')
C     READ(5,1082)SFACT
C1082 FORMAT(G7.2)
C     WRITE(5,108)
C108  FORMAT('  WHAT IS THE TIME INTERVAL DT [R] ')
C     READ(5,109)DT
C109  FORMAT(G5.3)
      TIME=750.
      DT=.1
      SFACT=100.
      NTIME=TIME
      XDT=DT/10.
C     START OF LOOP **************************************************
      IF (IPLOT.EQ.0)GOTD5
      CALL GGERA
      CALL GGBOX(7,0,0,767,479)
      CALL GGTEXT(7,626,475,XTEXT,1,0)
      CALL GGBOX(7,620,452,767,479)
C     PRINT INITIAL CONDITIONS****************************************
 5    T=T+DT
C     RATE EQUATIDNS**************************************************
      J=J0/(1+K13*Q1*Q4)
      POWUSE=100.*(J0-J)/J0
      PAVAIL=PAVAIL+J0
      EUSED=EUSED+J0-J
      R1=DT*K1*Q1*Q4*J
      R2=DT*K2*Q1
      R3=DT*K3*Q1
      R4=DT*K4*Q1
      R5=DT*K5*Q2
      R6=DT*K6*Q2
      R11=DT*K11*Q2
      R7=DT*K7*Q2*Q3*Q3
      R8=DT*K8*Q2*Q3*Q3
      R9=DT*K9*Q2*Q3*Q3
      R10=DT*K10*Q1*Q4*J
      R12=DT*K12*Q3
C     LEVEL EQUATIDNS ************************************************
 1091 CDNTINUE
      Q1=Q1+R1-R2
      Q2=Q2+R3-R9-R11
      Q3=Q3+R5+R7-R12
      Q4=Q4+R4+R6+R12+R8-R10
      IF(FT1(T,1.).GT.DT)GOTD 110
      IF(IPLOT.EQ.0)GOTD20000
      ITIME=T
      IXC=Q1/10.
```

```
      CALL GGPLT(4,ITIME,IXC,1)         !Q1 GREEN
      IXC=Q2/SFACT
      CALL GGPLT(3,ITIME,IXC,1)         !Q2 MAGENTA
      IXC=Q3/10.0
      CALL GGPLT(1,ITIME,IXC,1)         !Q3 BLUE
      IXC=Q4/100.
      CALL GGPLT(5,ITIME,IXC,1)         !Q4 CYAN
      IXC=(J0-J)*(250./J0)
      CALL GGPLT(2,ITIME,IXC,1)         !POWER USED RED
C
C     FINO WHICH Q TO SAVE IN ARRAY
20000 CONTINUE !GOTO(21000,22000,23000,24000,25000,26000)IQSAV
C     GOTO110
21000 IY(1,NRUN,INT(T/5.)+1)=INT(Q1/2.)
C     GOTO110
22000 IY(2,NRUN,INT(T/5.)+1)=INT(Q2/20.)
C     GOTO110
23000 IY(3,NRUN,INT(T/5.)+1)=INT(Q3/2.)
C     GOTO110
24000 IY(4,NRUN,INT(T/5.)+1)=INT(Q4/40.)
C     GOTO 110
25000 IY(5,NRUN,INT(T/5.)+1)=INT((J0-J)*5.)
C     GOTO110
26000 IY(6,NRUN,INT(T/5.)+1)=INT((POWUSE-80)*50)
 110  CONTINUE
      M1=AMAX1(M1,Q1)
      M2=AMAX1(M2,Q2)
      M3=AMAX1(M3,Q3)
      M4=AMAX1(M4,Q4)
      IF(T.LT.TIME)GOTO 5
C
      ENCODE(80,11003,YTEXT)NRUN,ALPHA(IVAL),VARS(IVAL)
     +,EUSED,100*EUSED/PAVAIL
11003 FORMAT(2X,I2,' VARIABLE ',A4,' = ',G15.4,' POWER USEO ',
     +G12.6,' PPU: ',G12.6)
      IF (IPLOT.EQ.0)WRITE(4,11004)YTEXT
11004 FORMAT(1X,80A1)
      IF (IPLOT.EQ.1)CALL GGTEXT(7,0,460,YTEXT,1,0)
      IF (ICOPY.EQ.1)WRITE(3,11001)
11001 FORMAT('+S(H)')
      IF(NRUN.LT.NSLICE)GOTO500
      IF (IPLOT.EQ.0)GOTO24999
      CALL GGERA
      CALL GGOFF
24999 IQSAV=1
24995 CONTINUE
      CALL ASSIGN(2,'PULSAV',6)
      ENCODE(40,25001,OES)IQSAV,FILE
25001 FORMAT(1X,' TANK Q',I1,' FOR OATA FILE ',3A4)
      WRITE(2)(OES(I),I=1,40),NRUN,NCNTS,
     + ((IY(IQSAV,J1,K),K=1,NCNTS),J1=1,NRUN)
      CLOSE(UNIT=2)
      IQSAV=IQSAV+1
      IF (IQSAV.LT.7)GOTO24995
```

```
C
C
      WRITE(4,114)
 114    FORMAT(//'            Q1        Q2        Q3        Q4    TOTAL')
      WRITE(4,1121)Q1IC,Q2IC,Q3IC,Q4IC,Q4IC+Q3IC+Q2IC+Q1IC
      WRITE(4,1122)M1,M2,M3,M4
      WRITE(4,1123)Q1,Q2,Q3,Q4,Q4+Q3+Q2+Q1
 1121   FORMAT(' INIT ',4(2X,G8.2),2X,G12.6)
 1122   FORMAT(' MAX  ',4(2X,G8.2))
 1123   FORMAT(' FINAL',4(2X,G8.2),2X,G12.6)
C
      WRITE(4,116)K1,K2,K3,K4,K5,K6,K7,K8,K9,K10,K11,K12,K13,J0,J
 116    FORMAT(/1X,'K1= ',G12.6,'   K2= ',G12.6,'   K3= ',G12.6/
     +' K4= ',G12.6,'   K5= ',G12.6,'   K6= ',G12.6/
     +' K7= ',G12.6,'   K8= ',G12.6,'   K9= ',G12.6/
     +' K10=',G12.6,'   K11=',G12.6,'   K12=',G12.6/
     +' K13=',G12.6,'   J0= ',G12.6,'   JR= ',G12.6)
      EUSED=EUSED*DT
      PAVAIL=PAVAIL*DT
      PPU=100.*EUSED/PAVAIL
      WRITE(4,119)VERS,DT,EUSED,PAVAIL,PPU
 119    FORMAT(/' PULSE MODEL VERS',F6.3,' TIME STEP(DT) = ',F6.4/
     +' TOTAL POWER USED   = ',G15.6,' POWER AVAILABLE =',G15.6/
     +' PERCENT POWER USED = ',G15.6)
      WRITE(4,120)(FILE(I),I=1,3),E1,E2,E3,E4,E5,E6,E7,E8,E9,E10,
     +E11,E12,E13,E14,E15
 120    FORMAT(' DATA FILE NAME = ',3A4,1X,15A4)
C
      IF(ICOPY.EQ.0)GOTO999
            CALL GGON
            WRITE(3,11001)
            CALL GGOFF
999   END
```

```
C       SURFACE PULSING MODEL PROGRAM  3/24/83
C       ADDITIDN OF CONSUMER CEILING TO ALLOW UP TD 100 TOTAL
C       CONSUMERS
C
C       DIFFUSIDN ADDED 7/21/83 TO NUTRIENT TANK Q4
C
C       VERS 3.01 ADDED STARTING CDNDITIDN TO FILE OUTPUT
C       VERS 3.02 ADD TIME AND DATE TD BEGINNING OF PROG
C
C
        PROGRAM SURPUL
C       Q1=PRODUCER
C       Q2=STORAGE (PRODUCER)
C       Q3=CONSUMER
C       Q4=NUTRIENTS
        DIMENSIDN Q1(12,12),Q4(12,12),E(12,12),Q3(100)
        DIMENSION Q4T(12,12)
        DIMENSION ETYPE(3),IX(144)
        DIMENSIDN Q2(12,12),IXYZ(100)
        INTEGER*4 ICNT(12,12)
        BYTE TITLE(10),ICDN(12,12),BUF1(9),BUF2(8)
        REAL M,K1,K2,K3,K4,K5,K6,K7,K8,K9,K10,MTDT
        REAL K11,K12,K13,J0,JR
        BYTE ESC,TEXT(80),COLOR,ICDLOR,CHAR
        INTEGER X1(100),Y1(100),T1,T2,XTEMP,YTEMP
        FT1(A,B)=ABS(AINT(A/B)-A/B)
        IXY(I,J)=(I-1)*12+J
        DATA TITLE/'D','S','P','1','0','0',' ',' ',' ',' '/
        DATA Q4T/144*0.0/                                   !DK
        DATA ICDN/144*0/
        DATA ETYPE(1)/'HIER'/
        DATA ETYPE(2)/'EVEN'/
        DATA ETYPE(3)/'RAND'/
        ESC=27
        VERS=3.02
        CALL TIME(BUF2)
        CALL DATE(BUF1)
        WRITE(5,5)ESC,ESC,ESC,ESC,TITLE,VERS,BUF2,BUF1  !3.0
5       FDRMAT(1X,A1,'PrTM1',A1,'®',A1,'[2J',A1,'[H',   !3.0
     &' SURFACE MODEL ',10A1,' --VERSION-- ',F5.2/      !3.0
     &1X,8A1,1X,9A1/                                    !3.02
     &' DD YOU WANT GRAPHICS DN (1-YES, 0-NO) '$)
        READ (5,6)IDFLAG
6       FORMAT(I1)
C
C
        WRITE (5,7)
7       FORMAT(' PLOTTING INTERVAL FOR PRODUCER AND CDNSUMER [I] '$)
        READ (5,8)ITINT,ITINTC
8       FDRMAT(I3,I3)
        WRITE(5,808)
808     FORMAT('  HARDCOPY AT PLOTTING INTERVAL (1-YES,0-ND)'$)
        READ(5,8081)IPTR
8081    FORMAT(I3)
```

```
      TINT=ITINT
      TINTC=ITINTC
      WRITE (5,81)
8082  CONTINUE
81    FORMAT('  HOW LONG TO RUN? [R] '$)
      READ (5,82)TTIME
82    FORMAT(G6.0)
      WRITE(5,83)
83    FORMAT(' WHAT IS DT [R] '$)
      READ (5,84)DT
84    FORMAT(G10.6)
      XDT=DT/TINT
      XDTC=DT/TINTC
      WRITE(5,841)                                           !DK
841   FORMAT(' WHAT IS NUTRIENT CONC. OF OUTER NONREACTIVE'/ !DK
    & '   RING (39000 IC; 0.0 TO ? ) [R] '$)                 !DK
      READ (5,842)Q4OIC                                      !DK
842   FORMAT(G16.5)                                          !DK
      WRITE(5,85)                                            !DK
85    FORMAT('  WHAT IS DIFFUSION COEFFICIENT? [R] '$)       !DK
      READ (5,86)DK                                          !DK
86    FORMAT(F8.5)                                           !DK
      WRITE(5,9)
9     FORMAT(' INPUT THE SEARCH LENGTH FOR PREDATOR [I] ',$)
      READ (5,11)N
11    FORMAT(I2)
      WRITE(5,91)
91    FORMAT(1X,' FEEDING AND DOUBLING THRESHOLD [R,R] '$)
      READ(5,92)PTHRSH,THRESH
92    FORMAT(2G8.2)
      WRITE(5,121)                                           !3.0
121   FORMAT(1X,'INPUT (0-SUCCESSION; 1-STEADY STATE) [I] '$) !3.0
      READ(5,122)ISSUC                                       !3.0
122   FORMAT(I2)                                             !3.0
      WRITE(5,12)
12    FORMAT(' WHAT ENERGY TYPE WOULD YOU LIKE'/
    + ' 1: STD INPUT'/
    + ' 2: CONSTANT INPUT'/
    + ' 3: RANDOM INPUT',20X,'ENERGY TYPE [I] '$)
      READ(5,13) IETYP
13    FORMAT(I1)
C     IF(IETYP.EQ.1)GOTO150
      WRITE(5,14)
14    FORMAT(' WHAT IS THE MEAN VALUE OF ENERGY '$)
      READ(5,15)XMEAN
15    FORMAT(F5.2)
150   CONTINUE
      GPP=0.          !GPP COUNTER (TOTAL)
      CNSUMP=0.       !CONSUMPTION BY CONSUMERS (TOTAL)
      Q1TOT=0.        !AMOUNT OF PRODUCERS
      Q2TOT=0.        !AMOUNT OF STORAGE
      Q3TOT=0.        !AMOUNT OF CONSUMERS
      Q4TOT=0.        !AMOUNT OF NUTRIENTS
      PROD=0.         !TOTAL PRODUCTION (GPP+CNSUMP)
```

```
      ETOT=0.           !TOTAL ENERGY INPUT (SUM OF MATRIX)
      TOTPOW=0.0        !MEASURE TOTAL POWER USED: SUM OF EUSED
      T=0.              !
      T1=1              !NUMBER OF CONSUMERS
      T2=T1
      Q1IC=1000.        !IC CONDITION FOR Q1
      Q4IC=39000.
      Q2IC=1000.
      IF(ISSUC.EQ.0)GOTO147                                       !3.0
      Q4IC=30000.       !IC CONDITION FOR NUTRIENT TANK           !3.0
      Q2IC=10000.       !IC FOR PRODUCER STORAGE                  !3.0
147   CONTINUE
      Q3IC=50.
C     THRESH=500.       !DOUBLING THRESHOLD FOR CONSUMER
      IF (IOFLAG.EQ.0)GOTO521
      CALL GGON
      IF (IPTR.EQ.0)GOTO151                                       !3.0
      WRITE(3,20171)
151   CALL GGINIT
      CALL GGAXIS(0,0,767,479)
      CALL GGERA
      CALL GGBOX(7,0,0,767,479)
      WRITE(3,51)
C
C     CLEAR MACROS AND DEFINE ONE TO DRAW BOXES
51    FORMAT('+','@. @:A P[+0,+0]W(S1)V[,+24]V[+24,]V[,-24]V[-24,]
    + W(S0) @;')
      WRITE (3,511)
511   FORMAT('+','@:B T(A1) P[+0,+0]V[,+24]V[+24,]V[,-24]V[-24,]
    + W(S0)T(A0) @;')
      WRITE(3,551)
551   FORMAT('+L(A1)'/
   +'+L"7"FFFFFFFFFFFFFFFFFFFF;'/
   +'+L"6"AA55AA55AA55AA55AA55;'/
   +'+L"5"92492492492492492492;'/
   +'+L"3"84210842108421084210;')
      WRITE(3,552)
552   FORMAT('+L"4"88442211884422118844;'/
   +'+L"2"42009100240091004200;'/
   +'+L"1"20000840021000042000;'/
   +'+L"0"00002000000200002000;'/
   +'+L"B"00000000000000000000;')
      DO 52 I=0,7
      CALL GGPLT(I,735,(I+1)*24-16,0)
      CHAR=I+48
52    WRITE(3,398)CHAR
      CALL GGBOX(7,725,0,767,248)
      CALL GGBOX(7,0,0,767,248)
      CALL GGBOX(7,575,0,725,248)
521   CONTINUE
C
C
C
C
```

```
C                       SET UP SURFACE OF FORCING ENERGY
      DATA TEXT/80*0/
      DATA E /0,0,0,0,0,0,0,0,0,0,0,0,
     + 0,0.8,0.8,0.8,0.8,0.8,0.8,0.8,0.8,0.8,0.8,0,
     + 0,0.8,1,1,1,1,1,1,1,1,0.8,0,
     + 0,0.8,1,1,1,1,1,1,1,1,0.8,0,
     + 0,0.8,1,1,1.2,1.2,1.2,1.2,1,1,0.8,0,
     + 0,0.8,1,1,1.2,1.2,1.2,1.2,1,1,0.8,0,
     + 0,0.8,1,1,1.4,1.4,1.4,1.4,1,1,0.8,0,
     + 0,0.8,1,1,1.2,1.2,1.2,1.2,1,1,0.8,0,
     + 0,0.8,1,1,1,1,1,1,1,1,0.8,0,
     + 0,0.8,1,1,1,1,1,1,1,1,0.8,0,
     + 0,0.8,0.8,0.8,0.8,0.8,0.8,0.8,0.8,0.8,0.8,0,
     + 0,0,0,0,0,0,0,0,0,0,0,0/
C
      X1(1)=5
      Y1(1)=5                  !SET PREDATOR CLOSE TO CENTER
      Q3(1)=Q3IC
      ICON(5,5)=1              !FIRST PREDATOR LOCATION
      IXYZ(1)=IXY(5,5)         !CODED LOCATION
      K1=.417E-5
      K2=.5
      K3=.05
      K4=.45
      K5=.5E-4
      K6=.45E-3
      K7=.2E-6
      K8=.18E-5
      K9=.2E-5
      K10=.417E-5
      K11=.5E-3
      K12=.05
      K13=.7833E-6
      DO 200 I=2,11
      DO 200 J=2,11
      Q1(I,J)=Q1IC
      Q2(I,J)=Q2IC
      Q4(I,J)=Q4IC
      E(I,J)=E(I,J)*100.
200   CONTINUE
      DO 201 IK=1,12                                            !DK
      Q4(1,IK)=Q4OIC                                            !DK
      Q4(12,IK)=Q4OIC                                           !DK
      Q4(IK,1)=Q4OIC                                            !DK
      Q4(IK,12)=Q4OIC                                           !DK
201   CONTINUE                                                  !DK

C
C     CHANGE ENERGY LEVEL?
C
      IF(IETYP.EQ.1)GOTO221
      DO 220 I=2,11
      DO 220 J=2,11
      E(I,J)=(XMEAN*RAN(-1)+.5)*100.  !SCALE RANDOM FUNCTION
```

```
      IF (IETYP.EQ.3)GOTO220
      E(I,J)=XMEAN*100.
220   CONTINUE
221   DO 250 I=2,11
      DO 250 J=2,11
      ETOT=ETOT+E(I,J)
250   CONTINUE
      IF (IETYP.EQ.2)GOTO300          !CHANGED 3 TO 2 IN 3.0
      SF=ETOT/(100.*100.)
      ETOT=0.0
      OO 270 I=2,11
      OO 270 J=2,11
      E(I,J)=E(I,J)*XMEAN/SF
      ETOT=ETOT+E(I,J)
270   CONTINUE
C
C
C>>>>>> LOOP START <<<<<<
C
300   CONTINUE         ! LOOP START
      IT=T             !GET INTEGER VALUE OF TIME FOR MOO FUNCTION
      EUSED=0.0        !ENERGY USEO PER TIME I.E. POWER
      SPTEMP=0.
      PTEMP=0.
      OO 400 I=2,11
      DO 400 J=2,11
C....  RATE EQUATIONS   ....
C
      I7=0
      INUM=0
      XEQ=0.0
C
      IF (ICON(I,J).NE.0)XEQ=1.0
      J0=E(I,J)
      JR=J0/(1+K13*Q1(I,J)*Q4(I,J))
      R1=DT*K1*Q1(I,J)*Q4(I,J)*JR
      R2=DT*K2*Q1(I,J)
      R3=DT*K3*Q1(I,J)
      R4=DT*K4*Q1(I,J)
      R5=OT*K5*Q2(I,J)
      R6=DT*K6*Q2(I,J)
      R10=OT*K10*Q1(I,J)*Q4(I,J)*JR
      R11=DT*K11*Q2(I,J)
      EUSED=EUSED+(J0-JR)*DT
C....  LEVEL EQUATIONS   ....
C
      PTEMP=PTEMP+R1                  !PRIMARY PROOUCTION

      Q1(I,J)=Q1(I,J)+R1-R2
      IF(Q1(I,J).LT.0.0)Q1(I,J)=0.0
      Q2(I,J)=Q2(I,J)+R3-R11
      Q4(I,J)=Q4(I,J)+R4+R6-R10
      Q4(I,J)=Q4(I,J)+R5*(1-XEQ)
C     ADD LINEAR FLOW TO Q4 IF Q3 NOT THERE
```

```
C
C....   CONSUMER CHECKING ROUTINE
C
        IF(XEQ.EQ.0)GOTO350                  !SKIP IF NO CONSUMER PRESENT
        IXYLOC=IXY(I,J)                      !GET CODED LOCATION
        INUM=1                               !AT LEAST ONE CONSUMER PRESENT
        DO 217 I7=1,T2                       !GET CONSUMER NUMBER
        IF (IXYZ(I7).NE.IXYLOC) GOTO217 !WRONG CONSUMER GOTO 217
C...    RATE EQUATIONS FOR CONSUMERS
C
        XDT=DT
C...    ...IF RATIO OF Q2/Q3 IS TOO LOW THEN ITERATE MORE SLOWLY
        IF(Q2(I,J)/Q3(I7).LT.5.0)XDT=.01
        DO 650 DDT=XDT,DT,XDT
        R7=XDT*K7*Q2(I,J)*Q3(I7)*Q3(I7)*XEQ
        R8=XDT*K8*Q2(I,J)*Q3(I7)*Q3(I7)*XEQ
        R9=XDT*K9*Q2(I,J)*Q3(I7)*Q3(I7)*XEQ
        R12=XDT*K12*Q3(I7)*XEQ

        SPTEMP=SPTEMP+R5*(XDT/DT)+R7              !SPTEMP = CONSUMP
C
C...    LEVEL EQUATIONS FOR CONSUMERS
        Q3(I7)=Q3(I7)+R5/(ICON(I,J))*(XDT/DT)+R7-R12
        Q2(I,J)=Q2(I,J)-R9                   !UPDATE PREY CONSUMED
        Q4(I,J)=Q4(I,J)+R8+R12               !UPDATE NUTRIENTS
650     CONTINUE
C
C
C
        IF((T-XTIME).LT.1.)GOTO217 !SKIP MOVEMENT IF NOT WHOLE DT
        XTIME=T
C       CHECK PRESENT POSITION FOR VALUE OF Q2
        QMAX=0
        IF(Q2(I,J).LT.PTHRSH)GOTO 1457
        XTEMP=X1(I7)
        YTEMP=Y1(I7)
        GOTO600
C  IF Q2 IS STILL CONSUMABLE DON'T MOVE, JUST EAT SOME MORE
1457    DO 600 I2=I-N,I+N
        DO 600 J2=J-N,J+N
        IF (I2.LT.1) GO TO 600
        IF (I2.GT.12) GO TO 600
        IF (J2.LT.1) GO TO 600
        IF (J2.GT.12) GO TO 600
        IF(Q2(I2,J2).LT.QMAX)GOTO580
          QMAX=Q2(I2,J2)
          XTEMP=I2
          YTEMP=J2
580     CONTINUE
600     CONTINUE
          ICON(I,J)=ICON(I,J)-1
C!REMOVE CONSUMER FROM PRESENT LOCATION
          ICON(XTEMP,YTEMP)=ICON(XTEMP,YTEMP)+1
C!MOVE CONSUMER TO NEW LOCATION
```

```
          IXYZ(I7)=IXY(XTEMP,YTEMP)
C!CODE NEW LOCATION
C
C...     CHECK TO SEE IF IT IS TIME TO REPRODUCE
C
         IF(Q3(I7).LT.THRESH)GOTO2000      !IF GREATER THAN REPRODUCTION
                T1=T1+1                    !INCREASE NUMBER OF CONSUMERS
                IF(T1.GT.100)GOTO2000      !ALLOW NO MORE THAN 100
                Q3(I7)=Q3(I7)/2.
                Q3(T1)=Q3(I7)
                X1(T1)=XTEMP
                Y1(T1)=YTEMP
                IXYZ(T1)=IXY(XTEMP,YTEMP)
                ICON(XTEMP,YTEMP)=ICON(XTEMP,YTEMP)+1
2000     CONTINUE
C
C
         X1(I7)=XTEMP
         Y1(I7)=YTEMP     !REM REMEMBER WHERE TO START NEXT TIME
C
C
2001     CONTINUE
C

217      CONTINUE

350      CONTINUE
C
C
400      CONTINUE
         GPP=GPP+PTEMP                      !ACCUMULATE TOTAL GPP
C
         T2=T1
         IF (T2.GE.100)T2=100
C
C
C        END CONSUMER LOOP AND DO BOOKEEPING
C
         CNSUMP=CNSUMP+SPTEMP
         PROD=GPP + CNSUMP
         TOTPOW=TOTPOW+EUSED
C
C        COUNT UP THE CONSUMERS
         NPROD=100
         IF(T2.LT.100)NPROD=T2
         Q3TOT=0.
         DO 453 I=1,NPROD
         Q3TOT=Q3TOT+Q3(I)
         ICNT(X1(I),Y1(I))=ICNT(X1(I),Y1(I))+1
453      CONTINUE
C
C        COUNT UP PRODUCERS AND NUTRIENTS
         Q1TOT=0.
         Q4TOT=0.
```

```
      Q2TOT=0.
      OO 4531 IX1=2,11
      DO 4531 IX2=2,11
      Q1TOT=Q1TOT+Q1(IX1,IX2)
      Q2TOT=Q2TOT+Q2(IX1,IX2)
      Q4TOT=Q4TOT+Q4(IX1,IX2)
4531  CONTINUE
      Q4TOUT=Q4(1,1)*44.
      TOT=Q1TOT+Q2TOT+Q3TOT+Q4TOT
      IF(IOFLAG.EQ.0)GOTO5000
C
C
C..... WRITE TEMPORARY INFORMATION AND PLOT GPP, POWER (EUSEO)
C
C
      IF ((T-PTIME1).LT.1.0)GOTO 5000
      PTIME1=T
      ENCODE(80,2006,TEXT)T,T2,EUSEO/(100.*DT),ETOT/100.,VERS,TITLE
     &,ETYPE(IETYP)
2006  FORMAT(1X,'T=',F6.2,' CONS=',I3,' POW USEO=',F6.2,
     & ' AVAIL POW= ',F6.2,' VER:',F5.2,1X,10A1,1A4)
      CALL GGTEXT(7,0,475,TEXT,1,0)
      IPT=PTEMP/(2.*OT*1000.)
      CALL GGPLT(4,IT,IPT+250,1)              !GREEN = GPP
      IPOWER=((EUSEO/(100.*XMEAN*DT))-80.)*5. !OUTPUT 80 TO 100
      CALL GGPLT(2,IT,IPOWER+250,1)           !REO = POWER
C
      ENCOOE(80,4532,TEXT)Q1TOT,Q2TOT,Q4TOT,Q3TOT,TOT
4532  FORMAT(1X,'Q1= ',F10.2,' Q2= ',F10.2,' Q4= ',F10.2,
     & ' Q3TOT= ',F10.2,' TOT= ',F10.2)
      CALL GGTEXT(6,0,460,TEXT,1,0)
      IYT=Q2TOT/20000.
      CALL GGPLT(3,IT,250+IYT,1)              !MAGENTA = PROOUCERS
      IYT=Q3TOT/200.+250.
      CALL GGPLT(7,IT,IYT,1)                  !WHITE =CONSUMERS
C
C     DRAW PROOUCERS
C-------------------------------------------------------
C                                                     !
      IF((T-PTIME).LT.TINT)GOTO4500                   !
      PTIME=T
      DO 4050 I=2,11                                  !
      OO 4050 J=2,11                                  !
      COLOR=Q2(I,J)/(2*1000.)         !3.0 CHANGED 4*1000 TO 2*1000
      IF(COLOR.GT.7)COLOR=7                           !
      IX9=I*24-40                                     !
      JY=J*24-44                                      !
      CHAR=48+COLOR                                   !
      IF(CHAR.GT.57)CHAR=57                           !
      CALL GGPLT(COLOR,IX9,JY,0)      !POINT TO LOWER LEFT
      WRITE(3,398)CHAR                                !
398   FORMAT('+','T(A1)W(S',1H',A1,1H',') @B')        !
399   FORMAT(' @A')                   !ORAW BOX (MACRO)
4050  CONTINUE                                        !
```

```
      CHAR='B'
      WRITE (3,3985)CHAR                                         !
      CALL GGPLT(0,600,10,0)
      CALL GGBOX(0,600,10,700,230)
      CALL GGFILL(0)
      CALL GGBOX(7,600,10,700,110)
      CALL SORT1(Q2,IX,144,400.)
        CALL GGPLT(7,601,IX(1)+10,1)
        DO 3991 IT1=2,100
        CALL GGVEC(3,600+IT1,IX(IT1)+10)
3991    CONTINUE
C                                                         !
C---------------------------------------------------------
C
4500  CONTINUE
C
C>>>>>> PLOT CONSUMERS <<<<<<
C---------------------------------------------------------------!
C                                                               !
      ICOLOR=0                                                  !
      IF((T-PTIMEC).LT.TINTC)GOTO 5000                          !
      PTIMEC=T
      CHAR='B'                                                  !
      WRITE (3,3985)CHAR                                        !
3985  FORMAT('+','T(A1)W(S',1H',A1,1H',')')                     !
      CALL GGBOX(ICOLOR,284,4,560,244)                          !
      CALL GGFILL(0)                                            !
      CALL GGPLT(7,0,0,1)
      CALL GGVEC(7,767,0)
      DO 2005 I1=1,T2                                           !
      ICOLOR=Q3(I1)/50.                                         !
      IF(ICOLOR.GT.7)ICOLOR=7                                   !
      CHAR=ICOLOR+48                                            !
      CALL GGPLT(ICOLOR,X1(I1)*24-4+284,Y1(I1)*24-44,0)         !
      WRITE(3,398)CHAR                                          !
2005  CONTINUE                                                  !
      CALL GGBOX(7,600,130,700,230)
      CALL SORT1(Q3,IX,T2,40.)
        CALL GGPLT(7,601,IX(1)+130,1)
        DO 2017 IT1=2,T2
        CALL GGVEC(7,600+IT1,IX(IT1)+130)
2017    CONTINUE
      IF(IPTR.EQ.0)GOTO5000
      WRITE (3,20171)
20171 FORMAT('+S(H)')
C                                                               !
C---------------------------------------------------------------!
C
C     SEE IF ITS TIME TO QUIT
5000  CONTINUE
C                                                               !DK
C     DIFFUSION                                                 !DK
C                                                               !DK
      QXT=0.0                                                   !DK
```

```
      DO 5002 I=2,11                                             !OK
      OO 5002 J=2,11                                             !OK
        DO 5001 IT=I-1,I+1                                       !OK
        OO 5001 JT=J-1,J+1                                       !OK
             QXT=QXT+DK*(Q4(IT,JT)-Q4(I,J))*DT                   !OK
5001    CONTINUE                                                 !OK
      Q4T(I,J)=Q4(I,J)+QXT                                       !OK
      QXT=0.0                                                    !DK
5002  CONTINUE                                                   !DK
      OO 5003 I=2,11                                             !OK
      OO 5003 J=2,11                                             !OK
      Q4(I,J)=Q4T(I,J)                                           !DK
5003  CONTINUE                                                   !DK
      T=T+DT
      IF(T.LT.TTIME)GOTO300
C>>>>>> END OF MAIN LOOP <<<<<<
C
      CALL GGOFF
      OO 439 I=1,12
      OO 439 J=1,12
      ICNT(I,J)=ICNT(I,J)*DT
439   CONTINUE
      CALL ASSIGN(4,'SURF4')
      WRITE(4,440)VERS,TITLE,BUF1,BUF2
440   FORMAT('1','SURFACE MODEL VERSION NO. ',F6.2,1X,10A1,
    & 1X,9A1,1X,8A1)
      WRITE(4,454)ETOT,ETYPE(IETYP),PROO,TOTPOW,TOTPOW/(TTIME*100.),
    & GPP,CNSUMP,N,ISSUC,OK
454   FORMAT(1X,' INPUT ENERGY TOTAL= ',F10.2,' ENERGY TYPE ',A4/
    & 1X,' TOTAL PROOUCTION =',G15.6/
    & 1X,' TOTAL POWER USEO =',G15.5,' AVE POWER/CELL = ',G15.6/
    & 1X,' GPP= ',G15.6,' TOTAL CONSUMPTION= ',G15.6/
    & 1X,' SEARCH LENGTH    =',I3,' STARTING CONDITION = ',I2/
    & 1X,' OIFFUSION COEFFICIENT = 'F7.5)
      WRITE(4,455)TTIME,DT,Q4TOT/1000.,Q4TOUT/1000.,
    &  (Q4TOUT+Q4TOT)/1000.
455   FORMAT(1X,' FOR ',F10.0,'ITERATIONS  DT= ',F7.3/
    & 1X,'            TOTAL NUTRIENTS (KG)  = ',F10.2/
    & 11X,'Q4 OUTER TOTAL (KG) = 'F10.2/
    & 11X,'TOTAL INNER AND OUTER (KG) = ',F10.2/
    & 1X,10X,' NUTRIENT MATRIX Q4(I,J)'/)
      WRITE(4,456)((Q4(I,J)/1000.,I=1,12),J=12,1,-1)
456   FORMAT(1X,12F7.2)
      WRITE(4,457)PTHRSH,THRESH,Q2TOT/1000.
457   FORMAT(//1X,'VALUES FOR Q2(I,J) PRODUCERS'/
    & 1X,'PROOUCER THRESHOLO FOR CONSUMER MOVING= ',F10.2/
    & 1X,'CONSUMER THRESHOLD FOR DIVIDING INTO  = ',F10.2/
    & 1X,'                    TOTAL PRODUCERS (KG)  = ',F10.2)
      WRITE(4,4561)((Q2(I,J)/1000.,I=2,11),J=11,2,-1)
4561  FORMAT(8X,10F7.2)
      WRITE(4,4581)
4581  FORMAT(//' CONSUMER VISITATION MATRIX '/)
      WRITE(4,4582)((ICNT(I,J),I=1,12),J=12,1,-1)
4582  FORMAT(12(1X,I6))
```

```
      WRITE(4,4584)
4584  FORMAT(//'  FINAL CONSUMER DISTRIBUTION')
      WRITE(4,4585)((ICON(I,J),I=1,12),J=12,1,-1)
4585  FORMAT(12(1X,I6))
      WRITE(4,4571)Q3TOT
4571  FORMAT(//1X,'VALUES FOR CONSUMERS TOTAL CONSUMERS =',G15.6)
      WRITE(4,458)((I,Q3(I),X1(I),Y1(I),IXYZ(I)),I=1,NPROD)
458   FORMAT(1X,I4,' Q3= ',F8.2,' X =',I2,'  Y =',I2,1X,I4)
      CALL CLOSE(1)
      END
C
C
C
      SUBROUTINE SORT1(X,IX,N,SF)
      DIMENSION X(1),IX(1)
      DO 20 I=1,N
      IX(I)=X(I)/SF
20    CONTINUE
      DO 40 I=1,N
      DO 40 J=I,N
      IF(IX(J).LT.IX(I))GOTO40
              ITEMP=IX(I)
              IX(I)=IX(J)
              IX(J)=ITEMP
40    CONTINUE
      RETURN
      END
```

```
        PROGRAM GRAPH2
C       vers RGRF
C
C       WRITTEN BY JOHN RICHARDSON
C
C       CALL TO REGLIN ADDED 6/15/83
C
C       MAXIMUM NUMBER OF DATA POINTS SET TO 250
C
C
C       MODIFIED 4/11/83 FOR RGL LIBRARY
C
        BYTE XTEXT(80),YTEXT(80),TITLE(80),ESC
        BYTE FNAME(16),IFNAM(16)
        LOGICAL IRFLAG,SMOOTH,SHADE
        DIMENSION X(250),Y(250),Y1(250)
        DATA TITLE/80*0/
        DATA XTEXT/80*0/
        DATA YTEXT/80*0/
        DATA FNAME/16*0/
        DATA IFNAM/16*0/
        ESC=27
        TYPE 10
10      FORMAT(' GRAPHING PROGRAM FOR GIGI'
     &/'          COMPLIMENTS OF JOHN RICHARDSON'/)
        WRITE(5,105)ESC,ESC
105     FORMAT(2X,A1,'PrTM1',A1,'®')
        TYPE 111
111     FORMAT(' PROGRAM REQUIRES THE TT: BUFFER BE SET TO NOWRAP'//
     &' SET /NOWRAP=TI:'//
     &' IF THIS IS NOT DONE PLEASE EXIT PROGRAM AND CORRECT THIS'//)
        TYPE 15
15      FORMAT('  IS DATA IN A DATA FILE? (1=YES, 0=NO, -1=EXIT) '$)
        ACCEPT 16,IANS1
16      FORMAT(I2)
        IF (IANS1.LT.0)STOP'MAKE CHANGES AND RERUN'
        IF (IANS1.EQ.0) GOTO 11
                TYPE 161
161             FORMAT(' FILE NAME FOR DATA: '$)
                ACCEPT 162, (FNAME(I),I=1,16)
162             FORMAT(16A1)
                OPEN(UNIT=1,NAME=FNAME,TYPE='OLD',FORM='FORMATTED')
                READ (1,1621)TITLE
1621            FORMAT(1x,80A1)
                WRITE(5,1621)TITLE
                READ(1,1622)NPAIRS
1622            FORMAT(1X,I3)
                DO 1630 I=1,NPAIRS
                READ(1,*)X(I),Y(I)
C1625           FORMAT(2G15.6)
1630            CONTINUE
                N=NPAIRS
                GOTO 51
11      TYPE 20
```

```
20      FORMAT('  HOW MANY PAIRS OF POINTS TO PLOT '$)
        ACCEPT 30,N
30      FORMAT(I3)
        IF(I.GT.500)GOTO11
        TYPE 35
35      FORMAT(1X,'DESCRIPTION OF DATA (UP TO 80 CHARACTERS '/)
        ACCEPT 36,(TITLE(K),K=1,80)
36      FORMAT(80A1)
        DO 50 I=1,N
59      TYPE 60,I
60      FORMAT('  X AND Y VALUES FOR POINT ',I3,
     &' SEPARATED BY COMMAS [R] ')
        READ (5,*,ERR=9911)X(I),Y(I)
50      CONTINUE
        CLOSE(UNIT=1)
                WRITE(5,601)
601             FORMAT(//1X,'DO YOU WANT TO SAVE DATA (1-YES, 0-NO)'$)
                READ(5,602)ISAVE
602             FORMAT(I1)
                IF (ISAVE.NE.1)GOTO51
                WRITE(5,603)
603             FORMAT('  WHAT IS THE FILE NAME FOR THE DATA '$)
                READ(5,604)IFNAM
604             FORMAT(16A1)
                CALL ASSIGN(2,IFNAM)
                WRITE(2,606)TITLE
606             FORMAT(1X,80A1)
                WRITE(2,608)N
608             FORMAT(1X,I3)
                DO 511 I=1,N
                WRITE(2,611)X(I),Y(I)
611             FORMAT(1X,G15.6,' , ',G15.6)
511             CONTINUE
                CLOSE(UNIT=2)
51      XMAX=0.
        YMAX=0.
        A=0.
        B=0.
        R2=0.
        CEE=0.
        TYPE 5001
5001    FORMAT(' DO YOU WANT TO RUN REGRESSION ON DATA? (1-YES, 0-NO)')
        ACCEPT 5002,IRGS
5002    FORMAT(I1)
        IF (IRGS.NE.0)CALL REGLIN(N,X,Y,A,B,R2,CEE)
        TYPE 501
501     FORMAT('  WHAT IT THE X- AXIS DESCRIPTION')
        ACCEPT 502,XTEXT
502     FORMAT(80A1)
        CALL STRIP(XTEXT,80)
        TYPE 503
503     FORMAT(' WHAT IS THE Y-AXIS DESCRIPTION')
        ACCEPT 504,YTEXT
504     FORMAT(80A1)
```

```
      CALL STRIP(YTEXT,80)
      TYPE 70
70    FORMAT(' WANT TO INPUT MINIMUMS AND MAXIMUMS (1-yes, 0-no)'$)
      ACCEPT 72,IMIN
72    FORMAT(I1)
      IF (IMIN.EQ.0)GOTO85
      TYPE 74
74    FORMAT(1X,'WHAT ARE XMIN AND XMAX [R] '$)
      ACCEPT *,XMIN,XMAX
      TYPE 76
76    FORMAT(1X,'WHAT ARE YMIN AND YMAX [R] '$)
      ACCEPT *,YMIN,YMAX
85    CONTINUE
      TYPE 89
89    FORMAT(1X,' LINE TYPE (0-9) '$)
      ACCEPT 891,ILIN
891   FORMAT(I1)
8910  TYPE 892
892   FORMAT(1X,'VALUE FOR DATA MARKER (0-9, -1 TO SEE LIST) '$)
      ACCEPT 893,IMARK
      IF(IMARK.GE.0)GOTO8930
      WRITE(5,8921)
8921  FORMAT(/' 0- POINT'
     & /' 1- SQUARE'
     & /' 2- OCTAGEN'
     & /' 3- TRIANGLE'
     & /' 4- CROSS'
     & /' 5- X'
     & /' 6- Y'
     & /' 7- DIAMOND'
     & /' 8- ARROWHEAD'
     & /' 9- HOURGLASS'
     & /' 10-POINT IN A CIRCLE')
      GOTO8910
8930  CONTINUE
893   FORMAT(I5)
      IF (IMIN.EQ.1)IROUND=0
      IF (IMIN.EQ.1)GOTO9910
      TYPE 90
90    FORMAT('  ROUND MAX AND MIN VALUES? (1-YES, 0-NO) '$)
      ACCEPT 99,IROUND
99    FORMAT(I1)
      IF(IROUND.GT.1)GOTO51
      IF(IROUND.LT.0)GOTO51
9910  IRFLAG=.FALSE.
      IF(IROUND.EQ.1)IRFLAG=.TRUE.
      WRITE (5,9901)
9901  FORMAT('  CURVEFIT THE DATA LINE (1-YES; 0-NO)'$)
      READ(5,9902)ISM
9902  FORMAT(I1)
      SMOOTH=.FALSE.
      IF(ISM.EQ.1)SMOOTH=.TRUE.
      WRITE(5,991)ESC
991   FORMAT('+'1A1,'[H')              !SEND CURSOR HOME
```

```
         SHADE=.FALSE.
         CALL INITGR(5)
         CALL CLRSCR
         CALL CLRTXT
         CALL SCOLOR('GRAY0',0)
         CALL SCOLOR('GRAY1',1)
         CALL SCOLOR('GRAY2',2)
         CALL SCOLOR('GRAY3',3)
         WRITE(5,991)ESC
         CALL OPAPER('LIN',10,2,'LIN',10,2,'GRAY3')
         IF (IMIN.EQ.0)GOTO1211
         CALL LNAXIS('YL',YTEXT,YMIN,YMAX,IRFLAG)
         CALL LNAXIS('XB',XTEXT,XMIN,XMAX,IRFLAG)
         GOTO1212
 1211    CALL LNAXIS('YL',YTEXT,,,IRFLAG)
         CALL LNAXIS('XB',XTEXT,,,IRFLAG)
         WRITE(5,991)ESC
 1212    CALL PDATA(N,X,Y,'L','GRAY2',IMARK,ILIN,SMOOTH,SHADE,0.0)
         IF(IRGS.EQ.0)GOTO1234
                 OO 1277 I1=1,N
                 Y1(I1)=B*X(I1)+A
 1277            CONTINUE
         CALL PDATA(N,X,Y1,'L','GRAY3',0,1,.FALSE.,.FALSE.,0.0)
         TYPE 121,ESC
         WRITE (5,1278)B,A,R2,CEE
 1278    FORMAT(/1X,' Y= ',G12.4,'*X + ',G12.4,' :R@2 = ',G12.4,
      +'STD ERR = ',G12.4)
 1234    TYPE 121,ESC
 121     FORMAT('+',1A1,'[H 0-QUIT; 1- REPLOT; 2-SCREENDUMP',$)
         ACCEPT 122, IANS
 122     FORMAT(I2)
         IF(IANS.EQ.1)GOTO 51
         IF (IANS.NE.2)GOTO 2550
         WRITE(5,1221)ESC
 1221    FORMAT('+',1A1,'[H',80X)
         CALL CPYSCR
         GOTO1234
2550     STOP 'END'
9911     WRITE(5,9912)
9912     FORMAT('  ERROR IN ENTRY PLEASE RE-ENTER')
         GOTO 59
         END
C
C
C
         SUBROUTINE STRIP (TEXT,N)
         BYTE TEXT(1)
         DO 20 I=N,1,-1
         IF (TEXT(I).EQ.32.OR.TEXT(I).EQ.0)GOTO20
                 TEXT(I+1)=0
                 RETURN
20       CONTINUE
         RETURN
         END
```

```
C
C
C
      SUBROUTINE REGLIN(N,X,Y,A,B,R2,CEE)
C
C     BASED ON PROGRAM IN 'COMMON BASIC PROGRAMS' BY
C     LON POOLE AND MARY BORCHERS P. 145
C
      DIMENSION X(1),Y(1)
      REAL J,K,L,M
C
C
      J=0.0
      K=0.0
      L=0.0
      M=0.0
      A=0.0
      B=0.0
      R2=0.0
      CEE=0.0
      DO 100 I=1,N
      J=J+X(I)
      K=K+Y(I)
      L=L+X(I)*X(I)
      M=M+Y(I)*Y(I)
      R2=R2+X(I)*Y(I)
100   CONTINUE
      XN=N
      B=(XN*R2-K*J)/(XN*L-J*J)
      A=(K-B*J)/XN
      J=B*(R2-J*K/XN)
      M=M-(K**2)/XN
      K=M-J
      R2=J/M
      CEE=SQRT(K/(XN-2))
      RETURN
      END
```

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